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# HUMAN FACTORS COMPARISON OF DIRECT AND LOR MODES (U)

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# FOREWORD

This report presents the results of a study performed under Contract No. NASw-533 for the NASA - Office of Human Factors by the Space and Information Systems Division of North American Aviation, Inc. The effects of crew and hardware reliability on the performance for a two-man, direct-flight Apollo mission and a three-man, lunar orbital rendezvous mission were compared.

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# 1.0 INTRODUCTION AND SUMMARY

A study has been completed to determine the relative influence of man's performance on mission success probability and crew safety for the Apollo lunar landing mission.

In this study a two-man direct flight (DF) mission is compared to a three-man lunar mission wherein two men land on the lunar surface via a lunar excursion module (LEM) that is launched after the spacecraft has been placed in lunar orbit. After the prescribed stay-time on the moon (24 hours), the LEM is launched from the lunar surface, performs a lunar orbit rendezvous (LOR) with the spacecraft, and the two men rejoin the third astronaut in command module (C/M).

The ground-rules employed in the study are as follows:

1. The spacecraft is launched from Cape Canaveral employing a three-stage Saturn C-5 vehicle capable of delivering 90,000 to 95,000 pounds to escape.

2. The spacecraft (consisting of the requisite command module (C/M), service module (S/M), and lunar excursion module (LEM) or lunar landing module (LLM) combinations) and spacecraft equipments (e.g., guidance, electronics, controls, life support, power supplies, etc.) were assumed to be those prescribed in the Apollo work statement. For the case of the three-man LOR mission, available data was employed from current NAA-S&ID Apollo designs for the C/M and S/M. Previous in-house studies were employed to generate data on the LEM and LLM. The two-man DF spacecraft configuration represented a scaled, preliminary design of a 120-inch-diameter Apollo C/M. S/M and LLM equipments were scaled and sized accordingly.

3. The LOR mission can be accomplished employing storable propellants in the S/M. The DF mission must employ a cryogenic oxidizer and fuel combination in order to stay below the assumed C-5 launch capability of 95,000 pounds to escape.

4. The outbound flight takes approximately 70 hours. Lunar stay time is in the order of 24 hours - with an emergency capability for another 24 hours, and the earthbound journey requires approximately 65 hours.

The study was developed as follows:

Crew Performance

Crew functions were generated from a time-line task and function analysis for each of the two modes considered. A set of standard or analogous tasks were defined in terms of crew tasks or functions in the Apollo and other manned space systems. A qualified panel ranked these tasks in the order of likelihood of successful accomplishment for four levels of increasing stress. Numerical values for each task were arrived at by establishing realistic upper and lower reliability limits and then converting the ranks for the standard tasks within these limits. Normal distributions were assumed in this conversion. Reliability values for each crew function in the LOR and DF mission were obtained by correlating the standard task to the analogous spacecraft crew function.

Mission Reliability

Mission success probabilities were determined by the application of a sophisticated computer program. This reliability analysis program, developed at NAA-S&ID for the Apollo, employs a Monte Carlo technique. A total of eight configurations were examined. The effects of in-flight maintenance and man's performance were examined for two conditions in each of the mission modes. Over 5,000 computer runs were made for each configuration. The results indicate that for the case of $R_{man} = 1$ there is essentially no significant difference in the mission success probability between the DF and LOR modes. Obviously, missions that have a maintenance capability yield a higher success probability than those which do not. For the case of $R_{man} < 1$, the mission success probability is degraded. The probability of completing the mission successfully in DF mode, however, is greater than that for the Apollo LOR mission.

Employing analytical techniques, three cases were examined for crew safety. One comparison was made between the DF and LOR missions for $R_{man} < 1$. The results indicated that, for the assumptions made, the 186-hour, Apollo DF mission was distinctly superior to the LOR mode. Another comparison considered the effect of maintenance with $R_{man} < 1$ for the DF mode. Again, crew safety probability was enhanced by employing the maintenance concept. Further study is required to determine the availability of sufficient room in the two-man Apollo C/M to affect requisite maintenance operations employing presently conceived replacement components. However, based upon the results of this study, the two-man DF mission even without maintenance appears to have a slight, but statistically significant, advantage over the three-man LOR mode. The data on mission success (MS) and crew safety (CS) are summarized in the following table.

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| Configurations | Two-Man DF Mission | | Apollo LOR Mission | |
|---|---|---|---|---|
| | MS | CS | MS | CS |
| $R_{man}$ = 1, w/o maint | 0.6791 | -- | 0.6709 | -- |
| $R_{man}$ = 1, w/maint | 0.7352 | -- | 0.7281 | -- |
| $R_{man}$ < 1, w/o maint | 0.5896 | 0.7689 | 0.5101 | -- |
| $R_{man}$ < 1, w/maint | 0.6756 | 0.8091 | 0.5658 | 0.7330 |

The studies showed that further enhancement of reliability could be obtained by diligent application of the in-flight maintenance concept in future studies. The Monte Carlo program identifies potential weaknesses in the complex sequence of events required for a successful mission; these weaknesses are then amenable to correction. Furthermore, the data shown are based on the launch-system data suggested in the NASA work statement. These appear somewhat conservative in light of recent tests. Possible overall reliability enhancement resulting from more optimistic booster data is discussed.

## Systems Consideration

Analysis showed that the two-man, DF mission would require cryogenic S/M and LLM propellants to stay within the 90,000- to 95,000-pounds weight-to-escape constraint of the C-5 vehicle. It also was shown that with a cryogenic system the base diameter of the C/M could be increased from the initially assumed 120-inches to the full 154-inches of the present Apollo and provide the two-man crew in the DF mission with a total of 238 cubic feet of habitable volume instead of the 82 cubic feet initially assumed. The cryogenic propellants offer a margin of more than 1500 pounds for the 120-inch, two-man, DF spacecraft. This margin also could be applied to increasing hardware reliability by increasing redundancy and the number of spare parts (at some reduction in the 238 cubic feet of habitable volume) for the eight day mission which employs present Apollo equipments.

Further study indicated that the reliability of cryogenic S/M and LLM propulsion systems could be made to approach that of a storable system within the development time period of interest. Inasmuch as a three-man, DF Apollo mission appears feasible with the C-5 in the late 1960's using improved state-of-the-art equipment if cryogenic S/M propellants are employed, it must be concluded that the mission success probability of the Apollo, as well as the crew safety, would be enhanced still further over the LOR mode by employing a three- rather than a two-man crew on a DF



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mission. The third man increases reliability by serving as a backup in case either crew member in the two-man mission is incapacitated. He also increases the scope of lunar surface operations.

The sections that follow describe in detail the human factors reliability considerations, the reliability analysis, and the system considerations. A glossary of the less than obvious abbreviations is given in Appendix A.



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## 2.0 HUMAN FACTORS CONSIDERATIONS

This section discusses crew function reliability for the LOR and DF missions, including the background considerations and the assumptions which formed the basis for these analyses. The discussion is divided into three sections:

1. Description of the procedures for development of crew function reliability data and resultant reliability estimates

2. Discussion of results

3. Background areas and assumptions

Crew-function reliability estimates were developed for spacecraft systems functions requiring direct and indirect participation by the crew. These data, when combined with data on the spacecraft hardware systems, were applied to determine probability of mission success and crew safety for the LOR and DF missions under consideration.

It should be noted that all references to mission phases in this section are in agreement with the LOR and DF mission profiles. All references to crew members pertain to the pilot commander (PC), the copilot (CP), and the systems manager (SM) for the LOR mission and to the PC and CP for the DF mission.

### 2.1 METHODOLOGY

Spacecraft systems functions were determined from the time-line phase analyses for each of the mission modes, and corresponding reliability estimates then were obtained. For each system function, corresponding crew functions were determined. To facilitate the estimation of crew reliability values, these crew functions subsequently were converted into task form. Numerical estimates of reliability for each crew function then were developed. These estimates were intended to represent the likelihood of crew performance success in the accomplishment of required mission functions.

The procedures for the generation of crew-function reliability estimates were developed considering the inherent limitations of time and the lack of applicable crew performance data. The procedure employed is explained in the following paragraphs.

Ten standard crew tasks, considered to be representative analogues of actual mission tasks, were constructed. The tasks were ranked by a qualified panel in order of relative difficulty considering performance time available and various fatigue levels. Reliability values then were assigned to each task, based upon the assumption of a normal distribution of the probability of successful performance. Analyses were made of the crew functions to establish the similarity between the actual mission task and a given standard task, and a reliability value was assigned for each corresponding crew function based on the value determined for the equivalent standard task. These data were incorporated into reliability models, wherein man was treated as a component, to determine mission success and crew safety probability.

The ten standard tasks were constructed to conform with currently conceived Apollo crew tasks and were designed to represent analogues of these crew tasks. The tasks were:

1. Precise control adjustments in sequence
2. Gross control and precise control under visual flight conditions while monitoring displays critical to the task
3. Switching in response to information obtained through monitoring
4. General monitoring of displays combined with switching to check certain systems in sequence
5. Switch in sequence
6. Gross control adjustments in sequence
7. Communicate information obtained by monitoring
8. Precise control adjustments while monitoring displays critical to the task
9. Gross control adjustments while monitoring displays critical to the task
10. General monitoring of displays while switching to check systems in no predetermined order

Each standard task was considered to be carried out under the following four conditions:

1. Ample time to perform the task, operator not fatigued

2. Barely time to perform the task, operator not fatigued

3. Ample time to perform the task, operator highly fatigued

4. Barely time to perform the task, operator highly fatigued

Four raters, all experienced in manned flight systems design and operation, were selected to rank the tasks in order of likelihood of operator failure under each of the four conditions. The raters were experienced pilots and instructors on single- and multi-engine propeller and jet aircraft. They are currently employed as research, spacecraft and human factors engineers. Their academic backgrounds include degrees in mechanical and aeronautical engineering, as well as psychology.

The orders of rank assigned were totaled for each standard task and each condition. On the basis of these totals, the standard tasks were ranked again on a 1 to 10 scale in order of greatest to least likelihood of operator failure under each condition, i.e., four rankings were obtained - one for each condition.

Two-place reliabilities were selected for each condition. These were based upon the Apollo crew functions; the expected qualifications, training, and motivation of the Apollo crew members; and the background considerations discussed in the sections that follow. The lower cutoff point of the distribution of estimated crew-function reliability selected for each condition is shown in the following list.

| Condition | Lower Cutoff Point |
|---|---|
| 1 | 0.99 |
| 2 | 0.98 |
| 3 | 0.97 |
| 4 | 0.96 |

The upper limit of the distribution for each condition was 1.0000. On the assumption of a normal distribution and an observed range of 5 sigma, the rank for each task and each condition was converted to a reliability figure. (It should be noted again that this procedure was a subjective one because of the inherent limitations described previously.)

The rationale behind the selection of cutoff points involved the assumption that the conditions of operation defined for the standard tasks were equally spaced in difficulty. It was considered that the most difficult standard task performed under optimal conditions would not be failed more than one time out of a hundred. It was also felt that, considering the extreme selection processes employed to choose the astronauts and the high levels of motivation under which they would perform, it is reasonable to expect that proper training and equipment design would yield a level of at least 0.96 operational proficiency for the time and fatigue stress conditions considered. The extreme task and condition combinations thus being set at 0.99 and 0.96, the intermediate task and condition combinations became – following the assumption of equally spaced difficulty – 0.97 and 0.98.

Each crew function was analyzed in terms of the standard tasks. The reliability figure for the standard task and condition that seemed the best analogue of the crew function under consideration guided the assignment of reliability to that crew function. Thus, each crew function was matched with a standard task considered and a condition considered to be most similar to the one under which the appropriate operation would be performed in the LOR or DF mission. Each crew function also was assigned an adjusted reliability in accordance with that of the standard task under the relevant condition. The adjustment of the reliability figure was made on a plus or minus five-point scale from the fourth figure of the standard task reliability. In cases where no standard task adequately represented the crew function, a reliability value was assigned on the basis of interpolation between applicable standard tasks or on the basis of subjective opinion.

## 2.2 RESULTS

Tables 1 through 4 represent the mission phase profiles and the function and phase relationships for the LOR and DF missions. Figures 1 through 4 show the stress-load profiles for the several conditions and the crew workload profiles. Tables 5 and 6 summarize the crew function reliabilities and reflect spacecraft systems functions as previously indicated. The first column of each table presents the crew function; the second column identifies the spacecraft system function – including primary (P) and alternate (A) modes where applicable; the third column indicates the pertinent mission phase for each function; and the final column presents the crew function reliability estimates. These tables contain the data that were employed to compute mission success and crew safety reliabilities that will be described in the section which follows.

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Table 1. Apollo 186-Hour Lunar Orbital Rendezvous Mission Phase Profile

| Phase Description | Initiation Time (Hr) | Termination Time (Hr) | Phase Time (Hr) |
|---|---|---|---|
| 1. Launch to jettison of LET | 0.0 | .042 | .042 |
| 2. LET jettison through second stage Boost | .042 | .140 | .098 |
| 3. Earth parking orbit | .140 | 1.273 | 1.133 |
| 4. Translunar injection | 1.273 | 1.373 | .100 |
| 5. LEM transfer | 1.373 | 1.873 | .500 |
| 6. First midcourse correction | 1.873 | 4.373 | 2.500 |
| 7. Translunar coast - Period No. 1 | 4.373 | 24.373 | 20.000 |
| 8. IMU alignment | 24.373 | 25.873 | 1.500 |
| 9. Translunar coast - Period No. 2 | 25.873 | 31.373 | 5.500 |
| 10. Translunar coast - Period No. 3 | 31.373 | 40.373 | 9.000 |
| 11. Navigation sightings No. 1 | 40.373 | 41.373 | 1.000 |
| 12. Translunar coast - Period No. 4 | 41.373 | 56.373 | 15.000 |
| 13. Navigation sightings No. 2 | 56.373 | 57.373 | 1.000 |
| 14. Translunar coast - Period No. 5 | 57.373 | 67.873 | 10.500 |
| 15. IMU alignment and navigation sightings | 67.873 | 70.440 | 2.567 |
| 16. Lunar orbit inject | 70.440 | 70.477 | .037 |
| 17. Lunar orbit | 70.477 | 72.297 | 1.820 |
| 18. LEM entry, checkout and separation | 72.297 | 73.077 | .780 |
| 19. LEM injection into elliptical orbit | 73.077 | 73.080 | .003 |
| 20. LEM approach operations | 73.080 | 73.577 | .497 |
| 21. LEM retrograde | 73.577 | 73.685 | .108 |
| 22. LEM hover and landing | 73.685 | 73.710 | .025 |
| 23. Lunar operations - Period No. 1 | 73.710 | 95.210 | 21.500 |
| 24. Lunar operation and lunar orbit correction | 95.210 | 97.710 | 2.500 |
| 25. Emergency lunar operations | 97.710 | 119.210 | 21.500 |
| 26. Lunar emergency orbit correction | 119.210 | 121.710 | 2.500 |
| 27. LEM lunar launch | 121.710 | 121.810 | .100 |
| 28. LEM rendezvous | 121.810 | 122.660 | .850 |
| 29. LEM docking and separation | 122.660 | 123.160 | .500 |
| 30. Post landing lunar orbit | 123.160 | 124.240 | 1.080 |
| 31. Transearth inject | 124.240 | 124.269 | .029 |
| 32. Transearth midcourse correction No. 1 | 124.269 | 127.269 | 3.000 |
| 33. Transearth coast - Period No. 1 | 127.269 | 150.269 | 23.000 |
| 34. Navigation alignment | 150.269 | 152.269 | 2.000 |
| 35. Transearth coast - Period No. 2 | 152.269 | 156.269 | 4.000 |
| 36. Navigation sightings - Transearth | 156.269 | 157.769 | 1.500 |
| 37. Transearth coast - Period No. 3 | 157.769 | 184.619 | 26.850 |
| 38. Final midcourse correction | 184.619 | 186.619 | 2.000 |
| 39. S/M separation | 186.619 | 186.629 | .010 |
| 40. Earth entry | 186.629 | 186.999 | .370 |
| 41. Deploy drogue chute through landing | 186.999 | 187.183 | .184 |

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Table 2. Two-Man, Direct-Flight, 186-Hour Mission Phase Profile

| Phase Description | Initiation Time (Hr) | Termination Time (Hr) | Phase Time (Hr) |
|---|---|---|---|
| 1. Launch to jettison of LET | 0.0 | .042 | .042 |
| 2. LET jettison through second-stage boost | .042 | .140 | .098 |
| 3. Earth parking orbit | .140 | 1.273 | 1.133 |
| 4. Translunar injection | 1.273 | 1.373 | .100 |
| 5. First midcourse correction | 1.373 | 3.873 | 2.500 |
| 6. Translunar coast - Period No. 1 | 3.873 | 24.373 | 20.500 |
| 7. IMU alignment | 24.373 | 25.873 | 1.500 |
| 8. Translunar coast - Period No. 2 | 25.873 | 31.373 | 5.500 |
| 9. Translunar coast - Period No. 3 | 31.373 | 40.373 | 9.000 |
| 10. Navigation sightings - No. 1 | 40.373 | 41.373 | 1.000 |
| 11. Translunar coast - Period No. 4 | 41.373 | 56.373 | 15.000 |
| 12. Navigation sightings - No. 2 | 56.373 | 57.373 | 1.000 |
| 13. Translunar coast - Period No. 5 | 57.373 | 67.873 | 10.500 |
| 14. IMU alignment and navigation sightings | 67.873 | 70.440 | 2.567 |
| 15. Lunar orbit inject | 70.440 | 70.477 | .037 |
| 16. Lunar orbit | 70.477 | 72.367 | 1.890 |
| 17. Descend to elliptical perilune | 72.367 | 73.350 | .983 |
| 18. Descend to 1000-feet altitude | 73.350 | 73.400 | .050 |
| 19. Hover and landing maneuver | 73.400 | 73.452 | .052 |
| 20. Lunar operations | 73.452 | 97.452 | 24.000 |
| 21. Emergency lunar operations | 97.452 | 121.452 | 24.000 |
| 22. Lunar launch - jettison LLM | 121.452 | 121.531 | .079 |
| 23. Lunar orbital maneuvers | 121.531 | 123.111 | 1.580 |
| 24. Transearth injection | 123.111 | 123.140 | .029 |
| 25. Transearth midcourse correction No. 1 | 123.140 | 126.140 | 3.000 |
| 26. Transearth coast - Period No. 1 | 126.140 | 149.140 | 23.000 |
| 27. Navigation alignment | 149.140 | 151.140 | 2.000 |
| 28. Transearth coast - Period No. 2 | 151.140 | 155.140 | 4.000 |
| 29. Transearth navigation sightings | 155.140 | 156.640 | 1.500 |
| 30. Transearth coast - Period No. 3 | 156.640 | 183.490 | 26.850 |
| 31. Final midcourse correction | 183.490 | 185.490 | 2.000 |
| 32. S/M separation | 185.490 | 185.500 | .010 |
| 33. Earth entry | 185.500 | 185.870 | .370 |
| 34. Deploy drogue chute through landing | 185.870 | 186.054 | .184 |



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## Table 3. Function and Phase Relationships for LOR Flight Missions

LEGEND:
ON +
OFF −

PHASE

1 LAUNCH TO JETTISON OF LET
2 LET JETTISON THROUGH SECOND STAGE BOOST
3 EARTH PARKING ORBIT
4 TRANSLUNAR INJECTION
5 LEM TRANSFER
6 FIRST MIDCOURSE CORRECTION
7 TRANSLUNAR COAST - PERIOD NO. 1
8 IMU ALIGNMENT
9 TRANSLUNAR COAST - PERIOD NO. 2
10 TRANSLUNAR COAST - PERIOD NO. 3
11 NAVIGATIONAL SIGHTING NO. 1
12 TRANSLUNAR COAST - PERIOD NO. 4
13 NAVIGATIONAL SIGHTINGS NO. 2
14 TRANSLUNAR COAST - PERIOD NO. 5
15 IMU ALIGNMENT AND NAVIGATIONAL SIGHTINGS
16 LUNAR ORBIT INJECT
17 LUNAR ORBIT
18 LEM ENTRY, CHECKOUT AND SEPARATION
19 LEM INJECTION INTO ELIPTICAL ORBIT
20 LEM APPROACH OPERATIONS
21 LEM RETROGRADE
22 LEM HOVER AND LANDING
23 LUNAR OPERATIONS PERIOD NO. 1
24 LUNAR OPERATIONS AND LUNAR ORBIT CORRECTION
25 EMERGENCY LUNAR OPERATIONS
26 LUNAR EMERGENCY ORBIT CORRECTION
27 LEM LUNAR LAUNCH
28 LEM RENDEZVOUS
29 LEM DOCKING AND SEPARATION
30 POSTLANDING LUNAR ORBIT
31 TRANSEARTH INJECT
32 TRANSEARTH MIDCOURSE CORRECTION NO. 1
33 TRANSEARTH COAST PERIOD NO. 1
34 NAVIGATION ALIGNMENT
35 TRANSEARTH COAST PERIOD NO. 2
36 NAVIGATION SIGHTINGS - TRANSEARTH
37 TRANSEARTH COAST PERIOD NO. 5
38 FINAL MIDCOURSE CORRECTION
39 S/M SEPARATION
40 EARTH ENTRY
41 DEPLOY DROGUE CHUTE THROUGH LANDING
OFF

| NO. | FUNCTION | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | OFF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | LAUNCH ESCAPE SYSTEM STRUCTURE | + | | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | C/M STRUCTURE | + | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | - |
| 3 | S/M STRUCTURE | + | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | - | | |
| 4 | ADAPTER STRUCTURE | + | | | | | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 5 | LEM STRUCTURE | + | | | | | | | | | | | | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | |
| 6 | LET JETTISON | | + | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | AC POWER INVERSION | + | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | | | | | | | | | |
| 8 | EPS MISSION SU | + | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | | | | | | | | | |
| 9 | EPS CREW SAFETY | | | | | | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | | | | - | | |
| 10 | EPS EARTH ENTRY | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | - |
| 11 | S/M RCS STORAGE | + | | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 12 | S/M RCS NEAR EARTH | | | + | | | | | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 13 | S/M RCS MISSION SU | | | | | | | | + | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | | | |
| 14 | S/M RCS CREW SAFETY | | | | | | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | | | | - | | |
| 15 | C/M RCS STORAGE TANK NO. 1 | + | | | | | | | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | | | |
| 16 | C/M RCS STORAGE TANK NO. 2 | + | | | | | | | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | | | |
| 17 | C/M RCS | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | - |
| 18 | S/M PROPULSION STGE | + | | | | | | | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | | | |
| 19 | S/M PROPULSION | | | | | | + | - | + | - | | + | - | + | - | + | | - | | | | | | | + | - | + | - | + | - | | + | | - | + | - | + | - | + | - | | | |
| 20 | C/M-S/M SEPARATION | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | - | | |
| 21 | EARTH-LANDING SYSTEM | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | - |
| 22 | MAIN CHUTE DEPLOYMENT | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | - |
| 23 | ECS | + | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | - | | | |
| 24 | ECS EARTH ENTRY | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | | - |
| 25 | LEM ADAPTER JETTISON | | | | | + | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 26 | LEM DOCKING ACTION | | | | | + | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 27 | LEM RCS CF27A | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | | | | | | | | | |
| 28 | LEM PROPULSION CF28A | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | | | | | | | | | |
| 29 | LEM ECS PRELANDING | | | | | | | | | | | | | | | | | | + | | | | | - | | | | | | | | | | | | | | | | | | | |
| 30 | LEM ECS LUNAR OPERATIONS | | | | | | | | | | | | | | | | | | | | | | | + | | - | | | | | | | | | | | | | | | | | |
| 31 | LEM ECS EMERGENCY LAND | | | | | | | | | | | | | | | | | | | | | | | | | + | | - | | | | | | | | | | | | | | | |
| 32 | LEM POSTLANDING ECS | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | | - | | | | | | | | | | | | |
| 33 | LEM GEAR JETTISON | | | | | | | | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | |
| 34 | LEM TELECOMMUNICATIONS | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | + | - | | | | | | | | | | | | |
| 35 | RADAR ALTIMETER | | | | | | | | | | | | | | | | | | | + | | | | - | | | | + | | - | | | | | | | | | | | | | |
| 36 | LEM EPS | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | - | | | | | | | | | | | | |
| 37 | LEM SCS | | | | | | | | | | | | | | | | | | + | | | | | - | | | | + | | - | | | | | | | | | | | | | |
| 38 | LEM N&G | | | | | | | | | | | | | | | | | | + | | | | | - | | | + | | | - | | | | | | | | | | | | | |
| 50 | S/C ELECTRONICS, NEAR-EARTH | | | + | | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 51 | S/C ELECTRONICS, TRANSLUNAR | | | | | | + | - | + | - | | + | - | + | - | + | | - | | | | | | | | | | | | | | | | | | | | | | | | | |
| 52 | S/C ELECTRONICS, LUNAR RENDEZVOUS | | | | | | | | | | | | | | | | | | | | | | | | | | + | | | - | | | | | | | | | | | | | |
| 53 | S/C ELECTRONICS, TRANSEARTH | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | | - | + | - | + | - | + | - | | | |
| 54 | S/C ELECTRONICS, EARTH-ENTRY | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | - |
| 55 | GOSS OPERATIONS | + | | - | | | | + | - | + | | - | + | - | + | - | | + | | | | | | | - | + | - | | | + | - | | | + | - | + | - | + | - | + | - | | |
| 80 | AC POWER INVERSION LUNAR LANDING | | | | | | | | | | | | | | | | | | | + | | | | - | | | | | | | | | | | | | | | | | | | |
| 81 | AC POWER INVERSION LUNAR OPERATIONS | | | | | | | | | | | | | | | | | | | | | | | | + | | | | | | - | | | | | | | | | | | | |
| 82 | AC POWER INVERSION TRANSEARTH | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | - |
| 83 | EPS LUNAR OPERATIONS | | | | | | | | | | | | | | | | | | | + | | | | | | - | | | | | | | | | | | | | | | | | |
| 84 | C/M RCS STORAGE NO. 1 | | | | | | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | | | | | | - |
| 85 | C/M RCS STORAGE NO. 2 | | | | | | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | | | | | | - |
| 86 | S/M PROPELLANT STAGE TRANSEARTH | | | | | | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | | | - | | | |
| 87 | LEM DOCKING ACTIVATOR LANDING | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | | | | | | | | | | |
| 88 | LEM DOCKING ACTIVATOR RENDEZVOUS | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | |
| 89 | LEM RCS APPROACH OPERATIONS | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | | | | | | | | |
| 90 | LEM RCS RETROGRADE | | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | | | | | | | |
| 91 | LEM RCS LANDING OPERATIONS | | | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | | | | | | |
| 92 | LEM RCS LAUNCH | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | - | | | | | | | | | | | | | |
| 93 | LEM PROPULSION, APPROACH OPERATIONS | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | | | | | | | | |
| 94 | LEM PROPULSION, RETROGRADE | | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | | | | | | | |
| 95 | LEM PROPULSION, LANDING OPERATIONS | | | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | | | | | | |
| 96 | LEM PROPULSION, LAUNCH | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | - | | | | | | | | | | | | | |
| 97 | LEM SCS, DOCKING AND SEPARATION | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | + | | | | | | | | | | | | |
| 98 | S/C ELECTRONICS, NEAR-EARTH | | | | | + | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

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# Table 4. Function and Phase Relationships for Two-Man, Direct Flight Missions

LEGEND:
ON +
OFF -

PHASE

| NO. | FUNCTION | 1 LAUNCH TO JETTISON OF LET | 2 LET JETTISON THROUGH SECOND-STAGE BOOST | 3 EARTH PARKING ORBIT | 4 TRANSLUNAR INJECTION | 5 FIRST MIDCOURSE CORRECTION | 6 TRANSLUNAR COAST - PERIOD NO. 1 | 7 IMU ALIGNMENT | 8 TRANSLUNAR COAST - PERIOD NO. 2 | 9 TRANSLUNAR COAST - PERIOD NO. 3 | 10 NAVIGATION SIGHTINGS - NO. 1 | 11 TRANSLUNAR COAST - PERIOD NO. 4 | 12 NAVIGATION SIGHTINGS - NO. 2 | 13 TRANSLUNAR COAST - PERIOD NO. 5 | 14 IMU ALIGNMENT AND NAVIGATION SIGHTINGS | 15 LUNAR ORBIT INJECT | 16 LUNAR ORBIT | 17 DESCEND TO ELLIPTICAL PERILUNE | 18 DESCEND TO 1000-FEET ALTITUDE | 19 HOVER AND LANDING MANEUVER | 20 LUNAR OPERATIONS | 21 EMERGENCY LUNAR OPERATIONS | 22 LUNAR LAUNCH - JETTISON LLM | 23 LUNAR ORBITAL MANEUVERS | 24 TRANSEARTH INJECTION | 25 TRANSEARTH MIDCOURSE CORRECTION NO. 1 | 26 TRANSEARTH COAST - PERIOD NO. 1 | 27 NAVIGATION ALIGNMENT | 28 TRANSEARTH COAST - PERIOD NO. 2 | 29 TRANSEARTH NAVIGATION SIGHTINGS | 30 TRANSEARTH COAST - PERIOD NO. 3 | 31 FINAL MIDCOURSE CORRECTION | 32 S/M SEPARATION | 33 EARTH ENTRY | 34 DEPLOY DROGUE CHUTE THROUGH LANDING | OFF |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | LAUNCH ESCAPE SYSTEM STRUCTURE | + | | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2 | C/M STRUCTURE | + | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | - |
| 3 | S/M STRUCTURE | + | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | - | | |
| 4 | LLM ADAPTER STRUCTURE | + | | | | | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | |
| 5 | LLM STRUCTURE | + | | | | | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | |
| 6 | LET JETTISON | | + | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | AC POWER INVERSION | + | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | | | | |
| 8 | EPS MISSION SUCCESS | + | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | | | | |
| 9 | EPS CREW SAFETY | | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | - | | |
| 10 | EPS EARTH ENTRY | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | - |
| 11 | S/M RCS STORAGE | + | | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 12 | S/M RCS NEAR EARTH | | | + | | | | | - | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 13 | S/M RCS SPACE | | | | | | | | + | | | | | | | | | | | | | - | | | | | | | | | | | | | | |
| 14 | S/M RCS CREW SAFETY | | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | - | | |
| 15 | C/M RCS STORAGE NO. 1 | + | | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | |
| 16 | C/M RCS STORAGE NO. 2 | + | | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | |
| 17 | C/M RCS | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | - |
| 18 | S/M PROPULSION STAGE | + | | | | | | | | | | | | | | | | | | | - | | | | | | | | | | | | | | | |
| 19 | S/M PROPULSION | | | | | | | | | | | | | | | | | | | | | | + | | | | - | + | - | + | - | + | - | | | |
| 20 | C/M-S/M SEPARATION | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | - | | |
| 21 | EARTH-LANDING SYSTEM | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | - |
| 22 | MAIN CHUTE DEPLOY | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | - |
| 23 | ECS | + | | | | | | | | | | | | | | | | | | | - | | + | | | | | | | | | | - | | | |
| 24 | ECS EARTH-ENTRY | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | | - |
| 25 | ECS PLANNED LUNAR OPERATIONS | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | |
| 26 | ECS EMERGENCY LUNAR OPERATIONS | | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | |
| 27 | LLM PROPULSION | | | | | + | - | + | - | | + | - | + | - | | | | | | | | | | | | | | | | | | | | | | |
| 28 | LLM ATTENUATION | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | | | | |
| 29 | LLM SEPARATION | | | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | |
| 30 | S/C ELECTRONICS, NEAR-EARTH | | | + | | - | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 31 | S/C ELECTRONICS, TRANSLUNAR | | | | | + | - | + | - | | + | - | + | - | + | | | - | | | | | | | | | | | | | | | | | | |
| 32 | S/C ELECTRONICS, LUNAR LANDING AND LAUNCH OPERATIONS | | | | | | | | | | | | | | | | | + | | | - | | + | - | | | | | | | | | | | | |
| 33 | S/C ELECTRONICS, TRANSEARTH | | | | | | | | | | | | | | | | | | | | | | | + | | | - | + | - | + | - | + | - | | | |
| 34 | S/C ELECTRONICS, EARTH-ENTRY | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | + | | | - |
| 35 | GOSS OPERATIONS, NONCRITICAL | + | | - | | | + | - | + | | - | + | - | + | - | | | | | | + | | - | | | | + | - | + | - | + | - | | | | |
| 80 | LUNAR LANDING AC POWER INVERSION | | | | | | | | | | | | | | | | | + | | | - | | | | | | | | | | | | | | | |
| 81 | LUNAR LAUNCH AC POWER INVERSION | | | | | | | | | | | | | | | | | | | | | | + | - | | | | | | | | | | | | |
| 82 | TRANSEARTH AC POWER INVERSION | | | | | | | | | | | | | | | | | | | | | | | + | | - | | | | | | | | | | |
| 83 | EPS MISSION SUCCESS | | | | | | | | | | | | | | | | | + | | | | - | | | | | | | | | | | | | | |
| 84 | C/M RCS STORAGE NO. 1 | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | | | | - |
| 85 | C/M RCS STORAGE NO. 2 | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | | | | - |
| 86 | S/M PROPULSION STAGE | | | | | | | | | | | | | | | | | | | | + | | | | | | | | | | | | - | | | |

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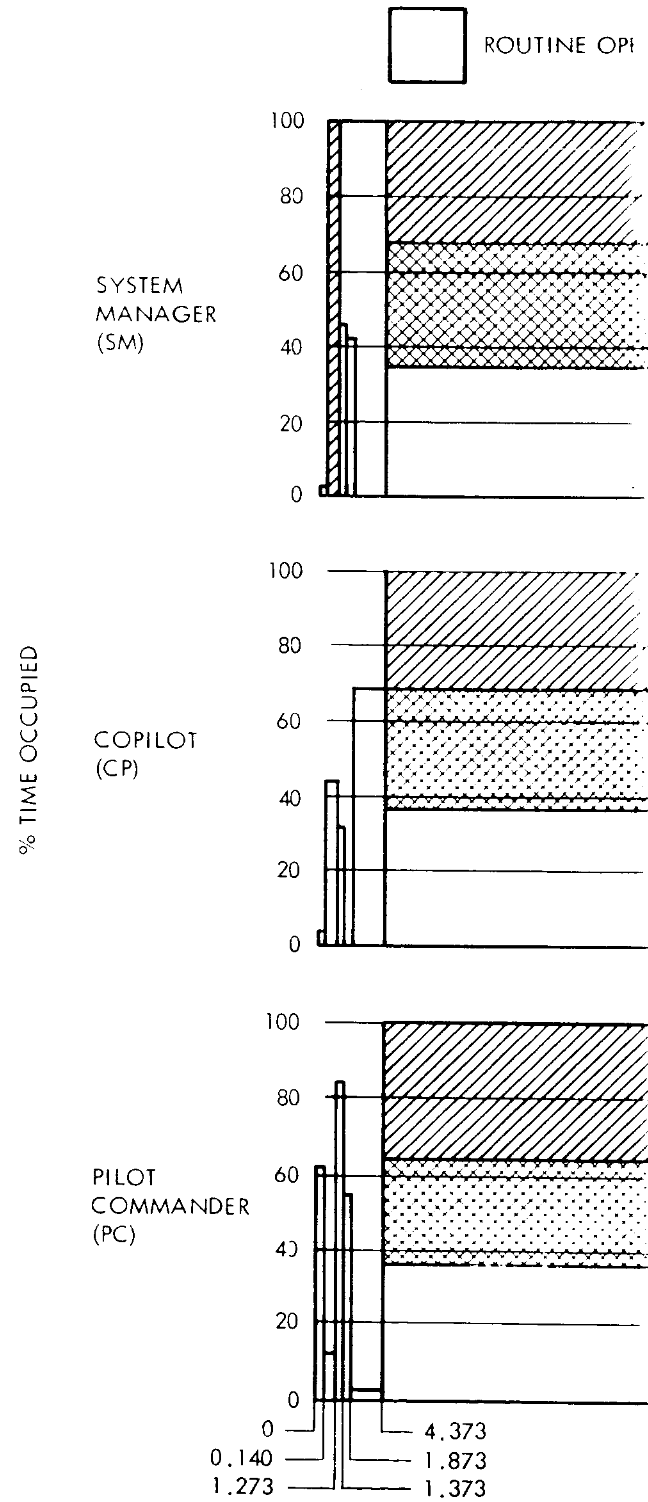
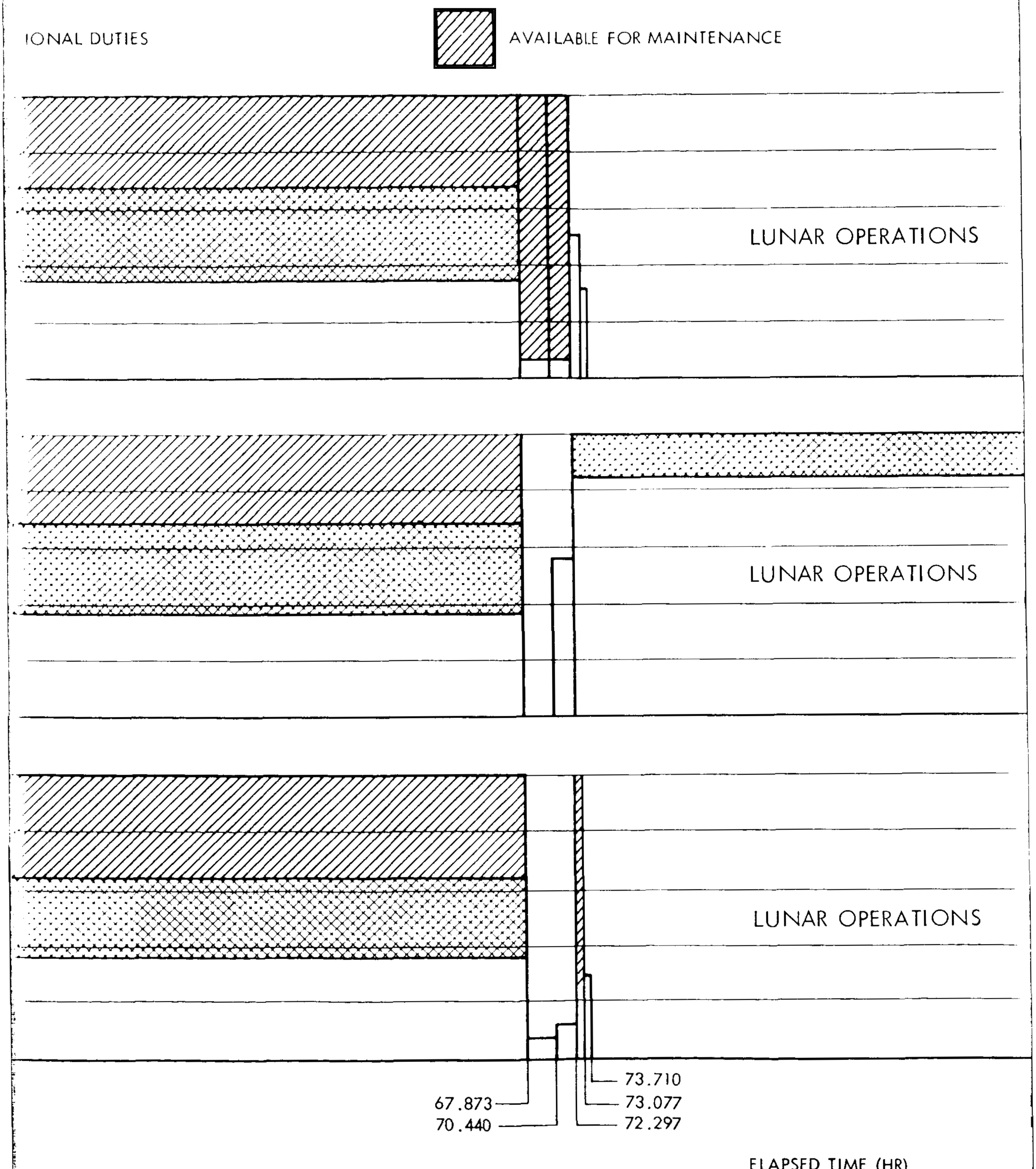
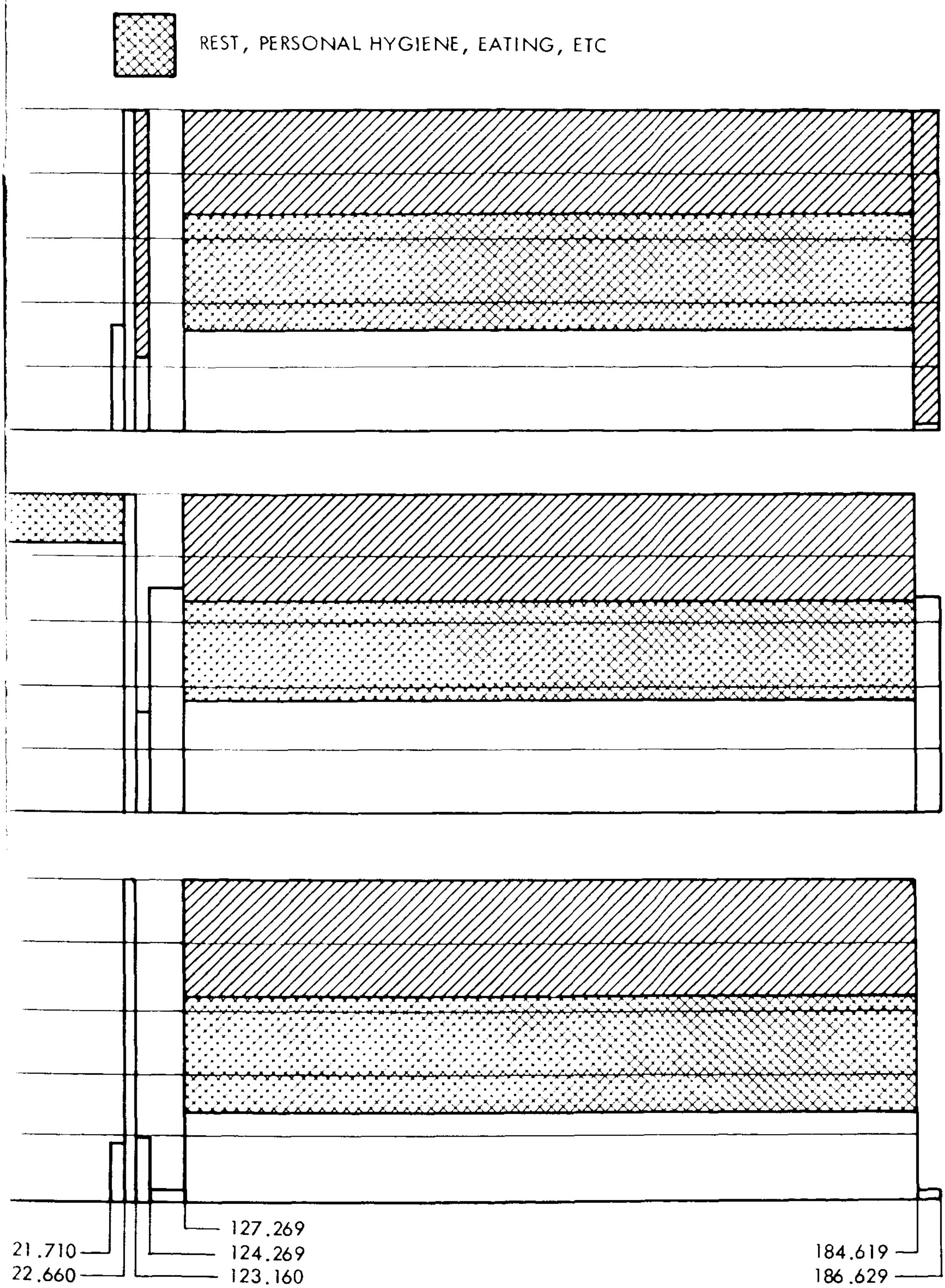


ROUTINE OP
% TIME OCCUPIED
SYSTEM MANAGER (SM)
COPILOT (CP)
PILOT COMMANDER (PC)
100
80
60
40
20
0
0
0.140
1.273
4.373
1.873
1.373


IONAL DUTIES
AVAILABLE FOR MAINTENANCE
LUNAR OPERATIONS
LUNAR OPERATIONS
LUNAR OPERATIONS
73.710
67.873
73.077
70.440
72.297
ELAPSED TIME (HR)

Figu




re 1. Crew Work Load—Lunar Orbital Rendezvous Mission

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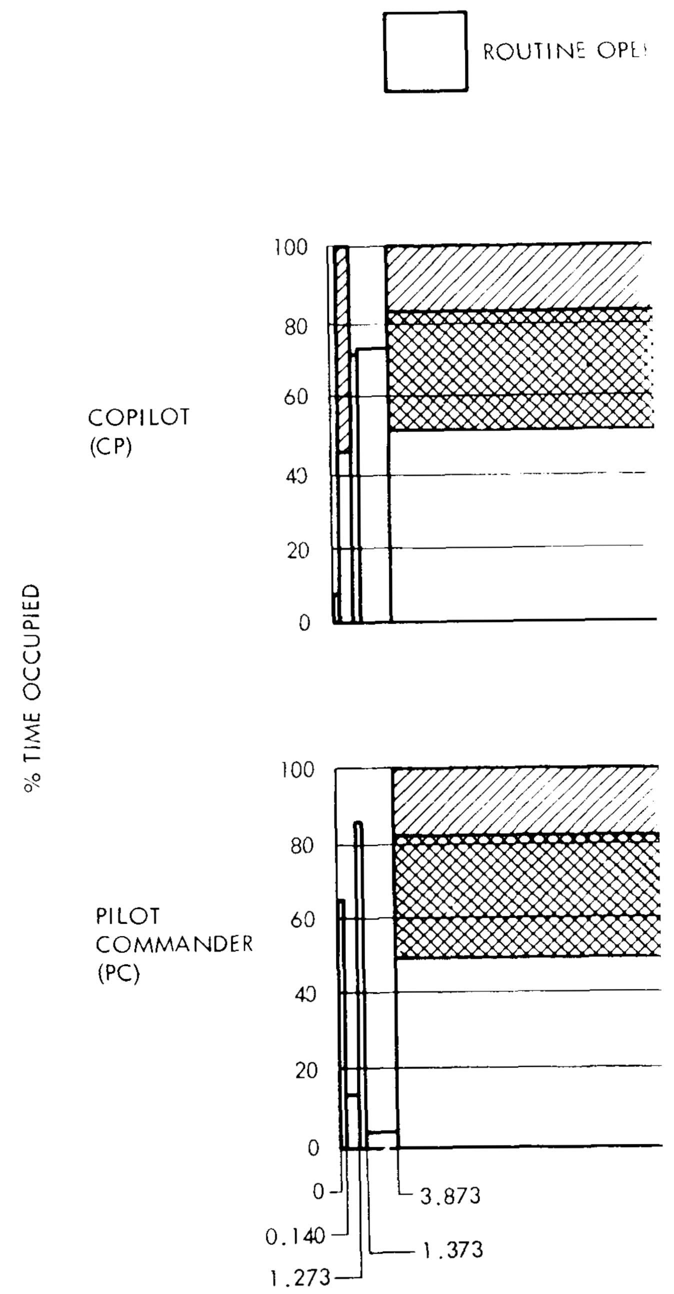
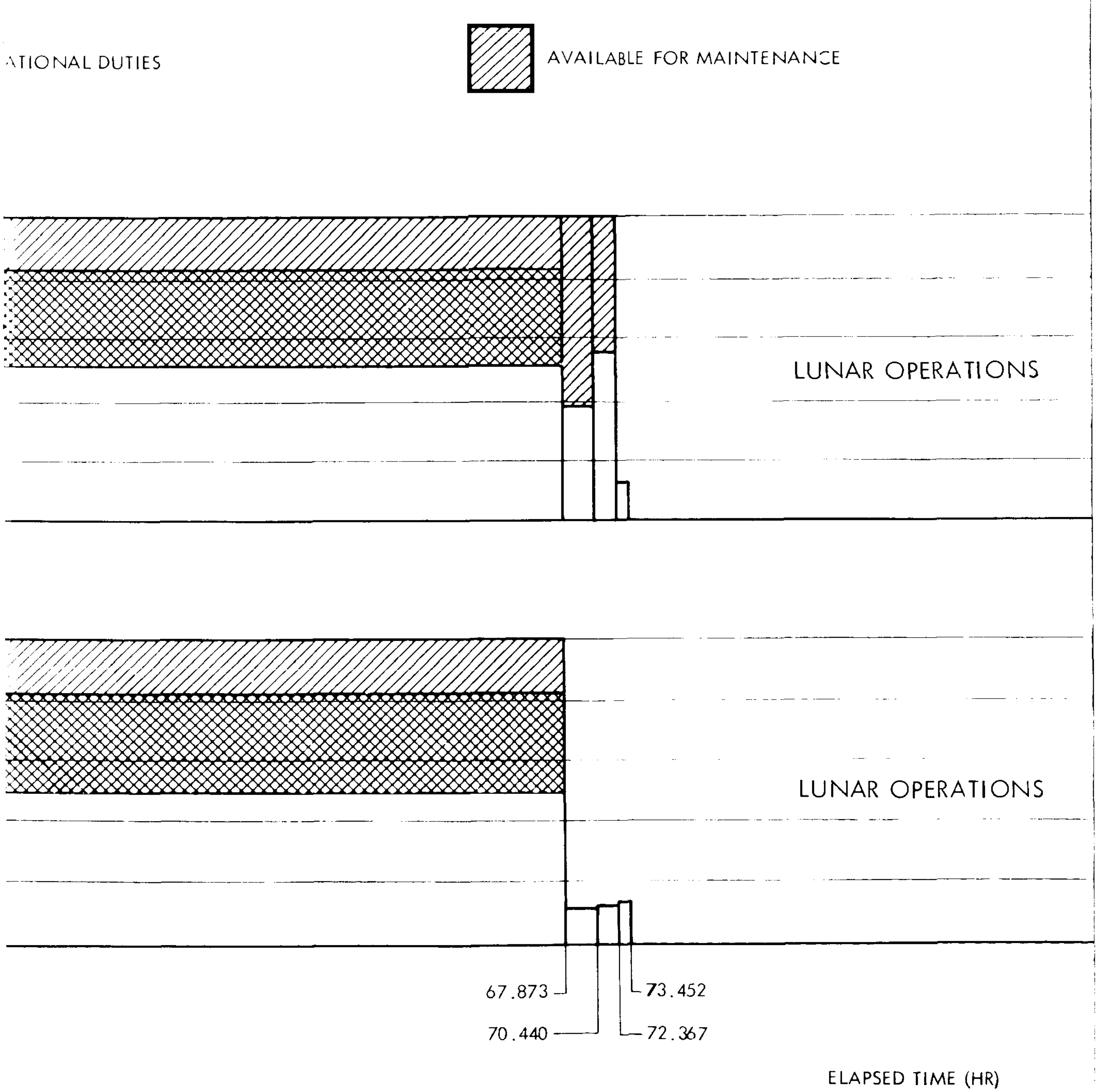


ROUTINE OPE
% TIME OCCUPIED
COPILOT
(CP)
100
80
60
40
20
0
PILOT
COMMANDER
(PC)
100
80
60
40
20
0
0
0.140
1.273
1.373
3.873


ATIONAL DUTIES
AVAILABLE FOR MAINTENANCE
LUNAR OPERATIONS
LUNAR OPERATIONS
67.873
70.440
73.452
72.367
ELAPSED TIME (HR)

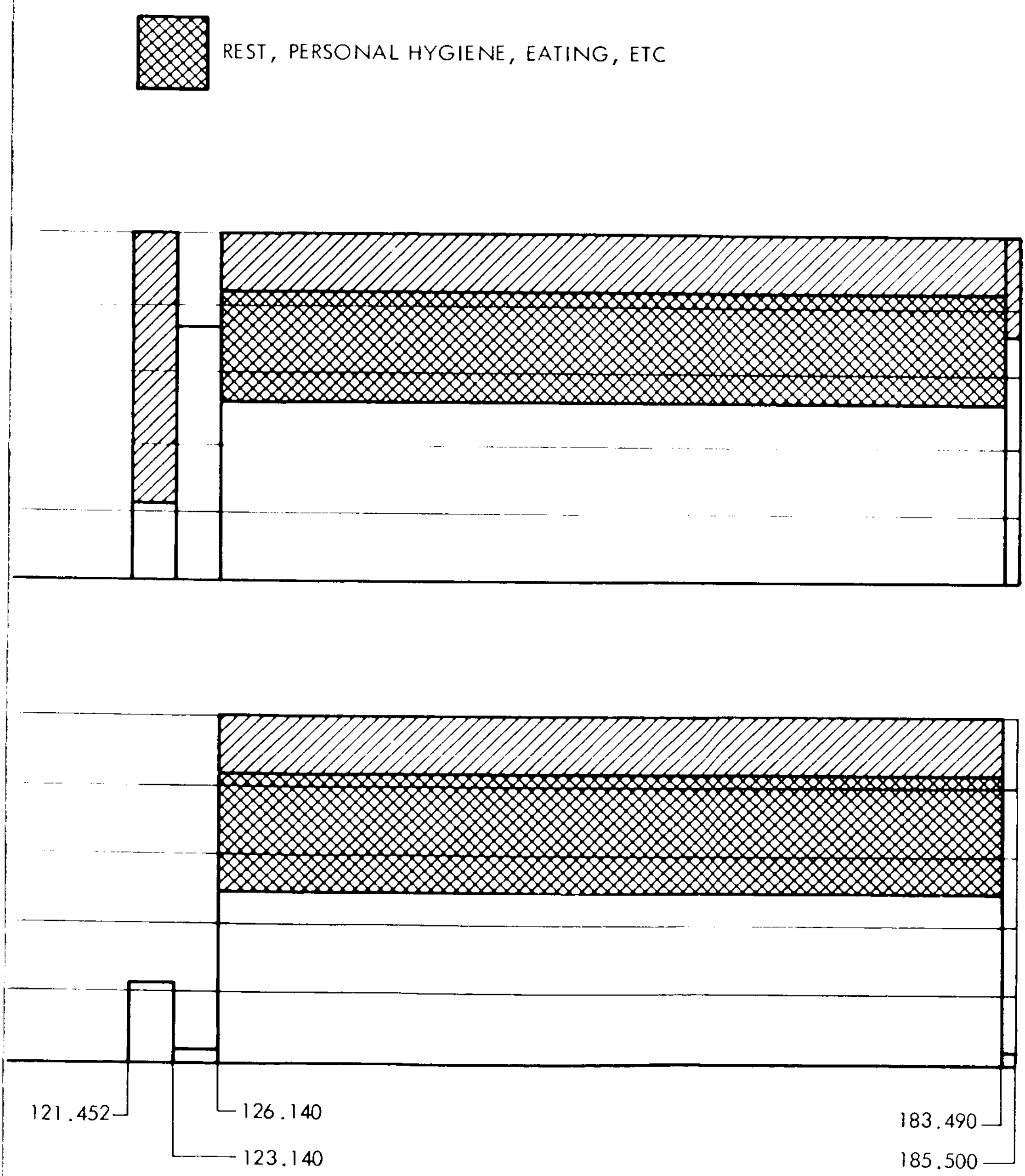



Figure 2. Crew Work Load—Direct Flight Mission



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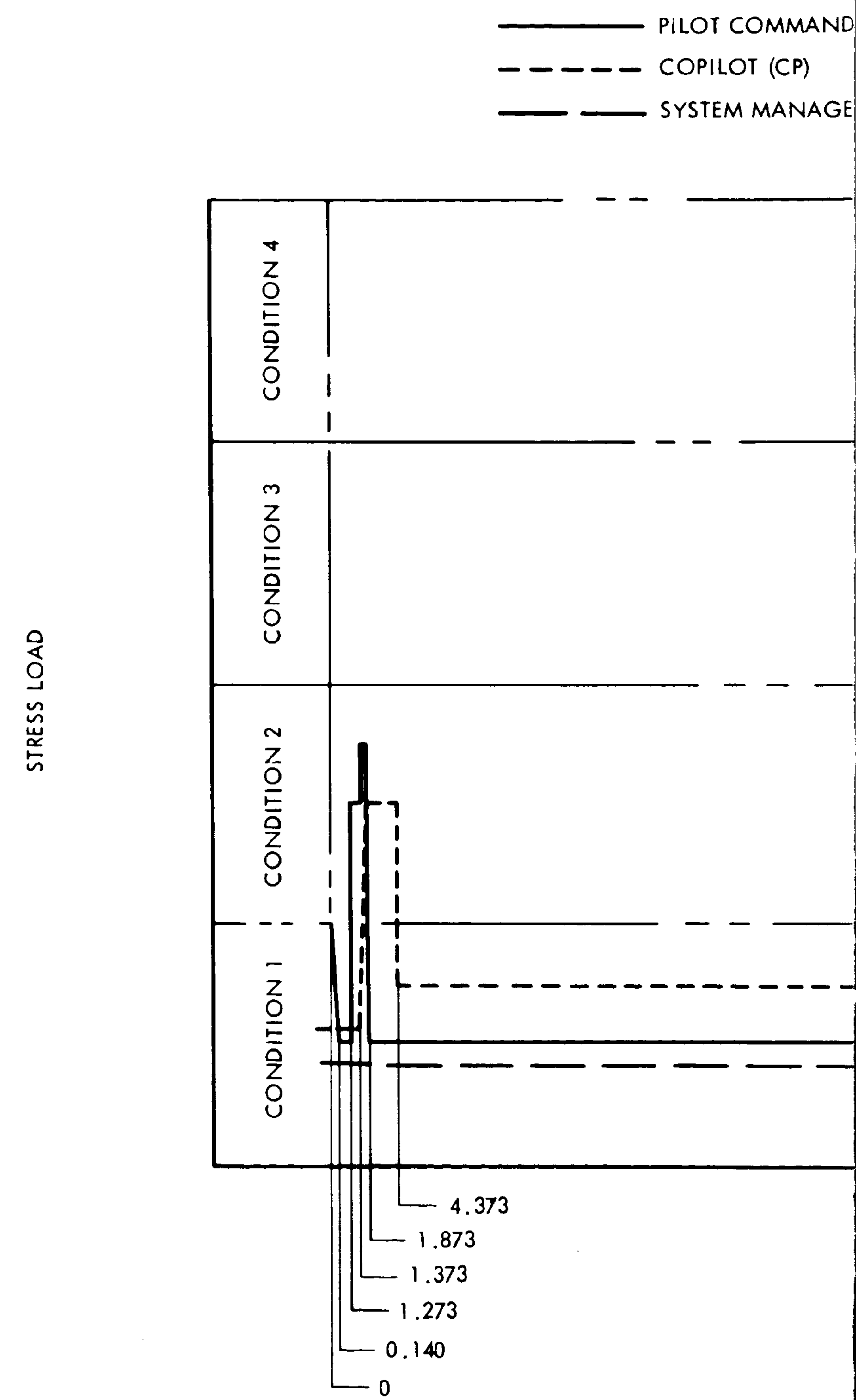
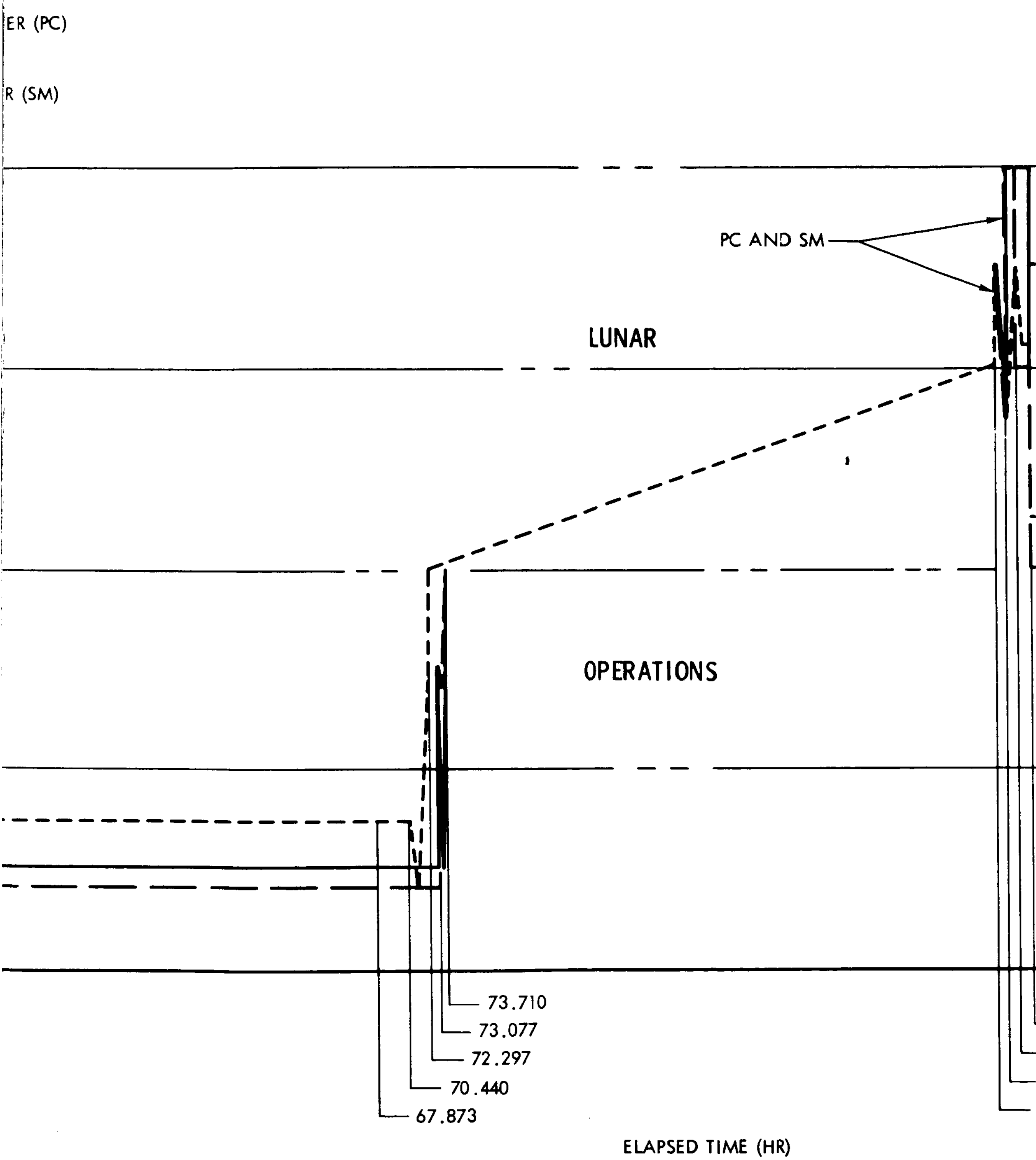


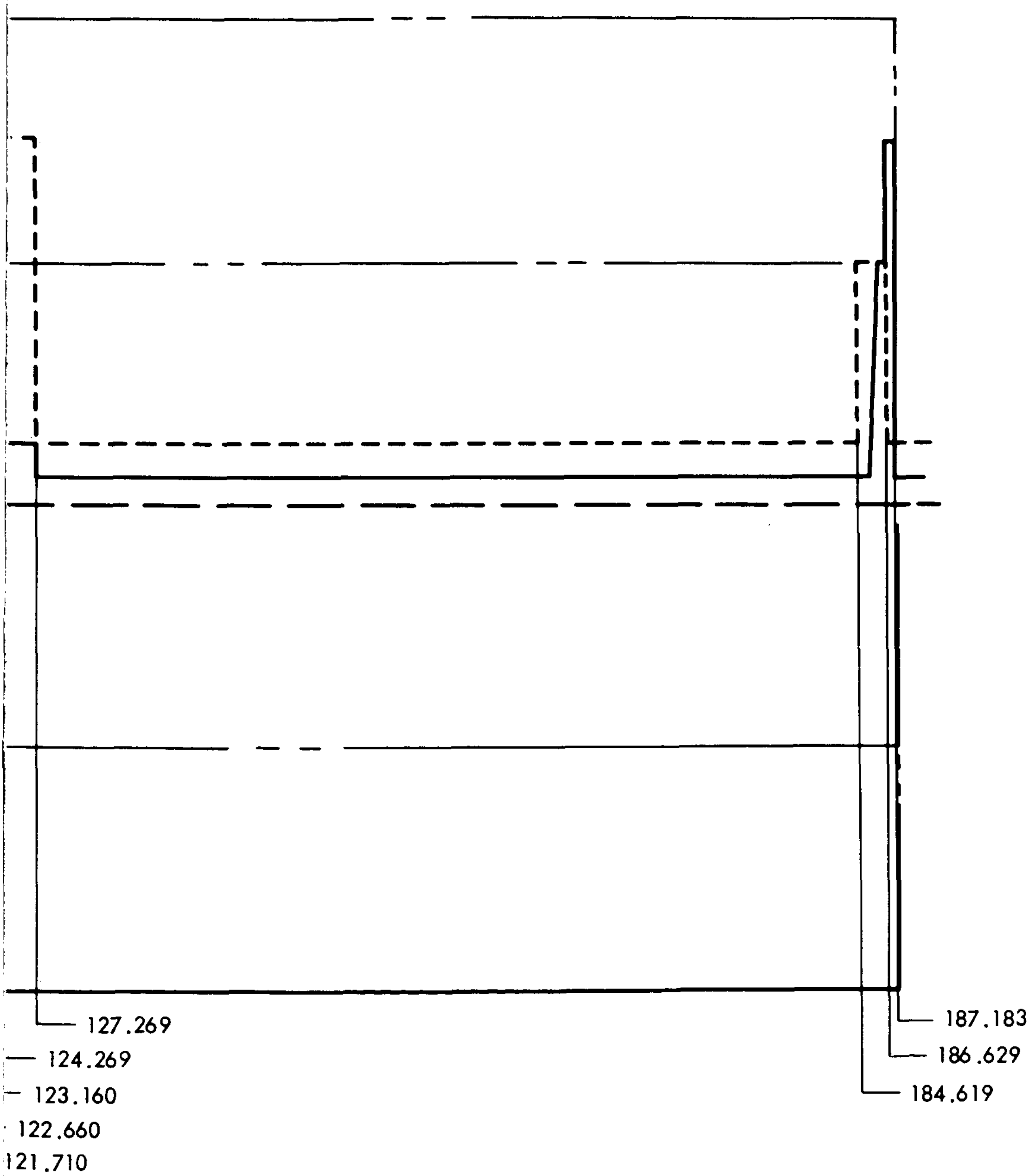
PILOT COMMAND
COPILOT (CP)
SYSTEM MANAGE
STRESS LOAD
CONDITION 4
CONDITION 3
CONDITION 2
CONDITION 1
4.373
1.873
1.373
1.273
0.140
0

NORTH



ER (PC)
R (SM)
PC AND SM
LUNAR
OPERATIONS
73.710
73.077
72.297
70.440
67.873
ELAPSED TIME (HR)


F




gure 3. Crew Stress Load—Lunar Orbital Rendezvous Mission

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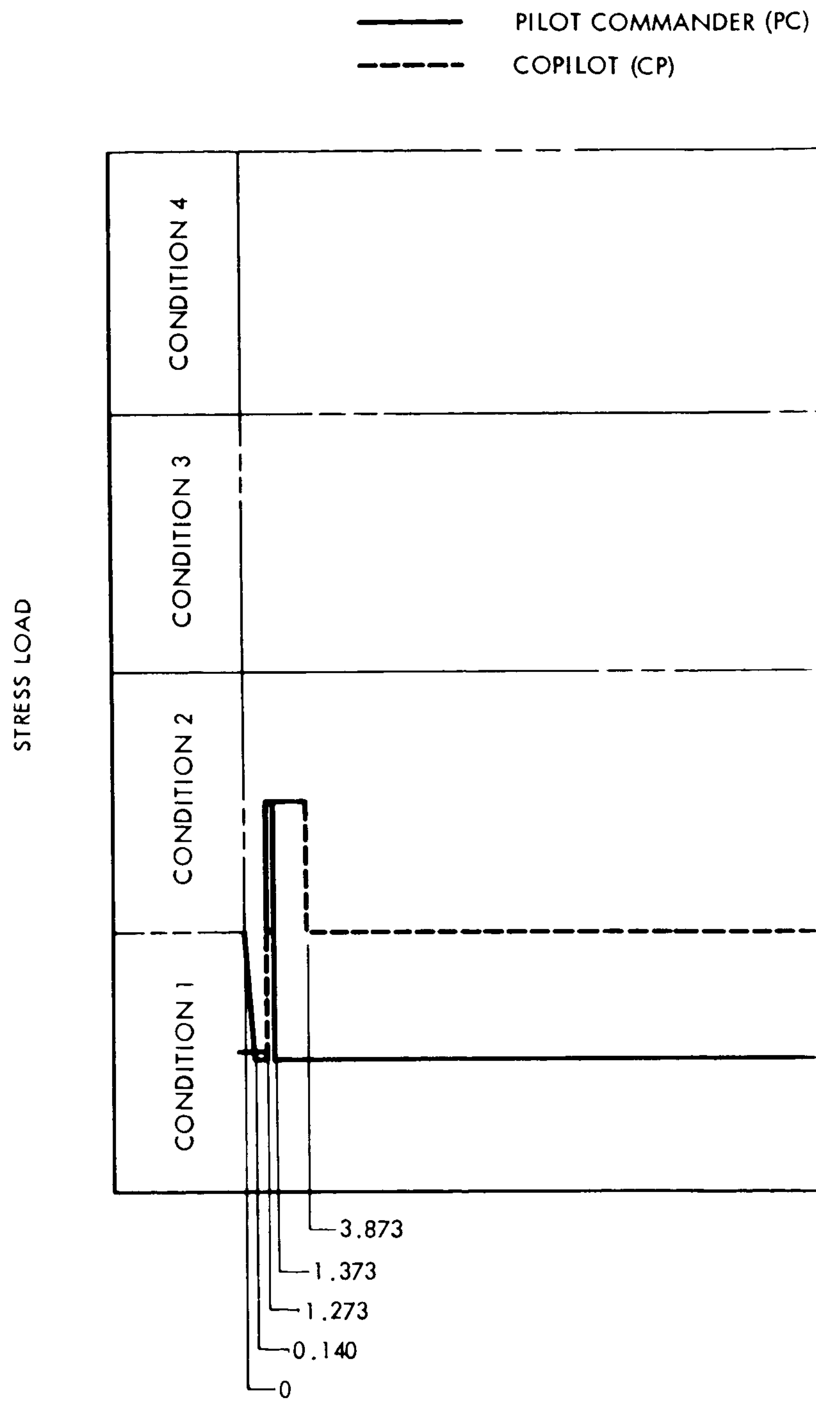
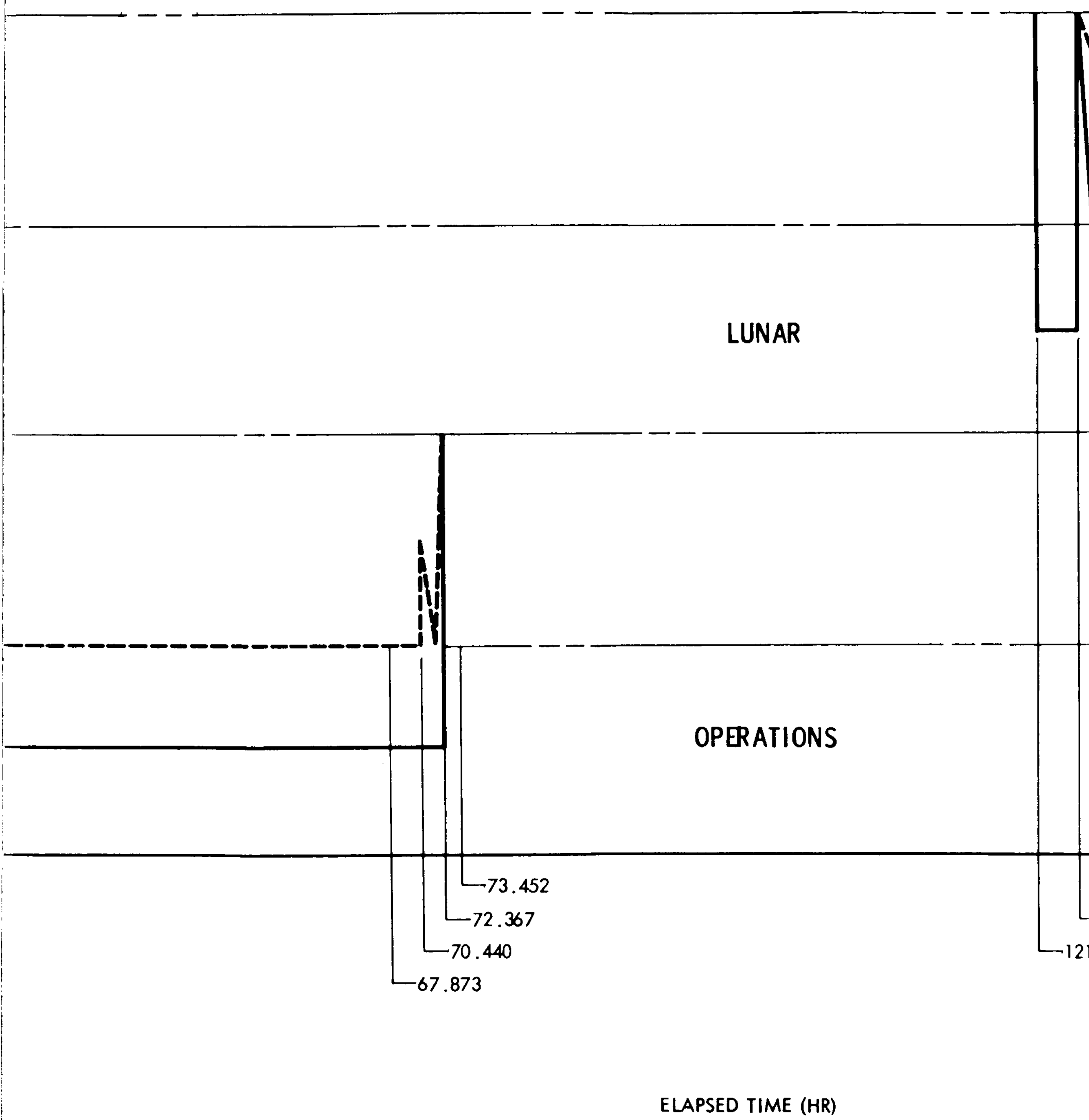


PILOT COMMANDER (PC)
COPILOT (CP)
STRESS LOAD
CONDITION 4
CONDITION 3
CONDITION 2
CONDITION 1
3.873
1.373
1.273
0.140
0


LUNAR
OPERATIONS
73.452
72.367
70.440
67.873
121
ELAPSED TIME (HR)

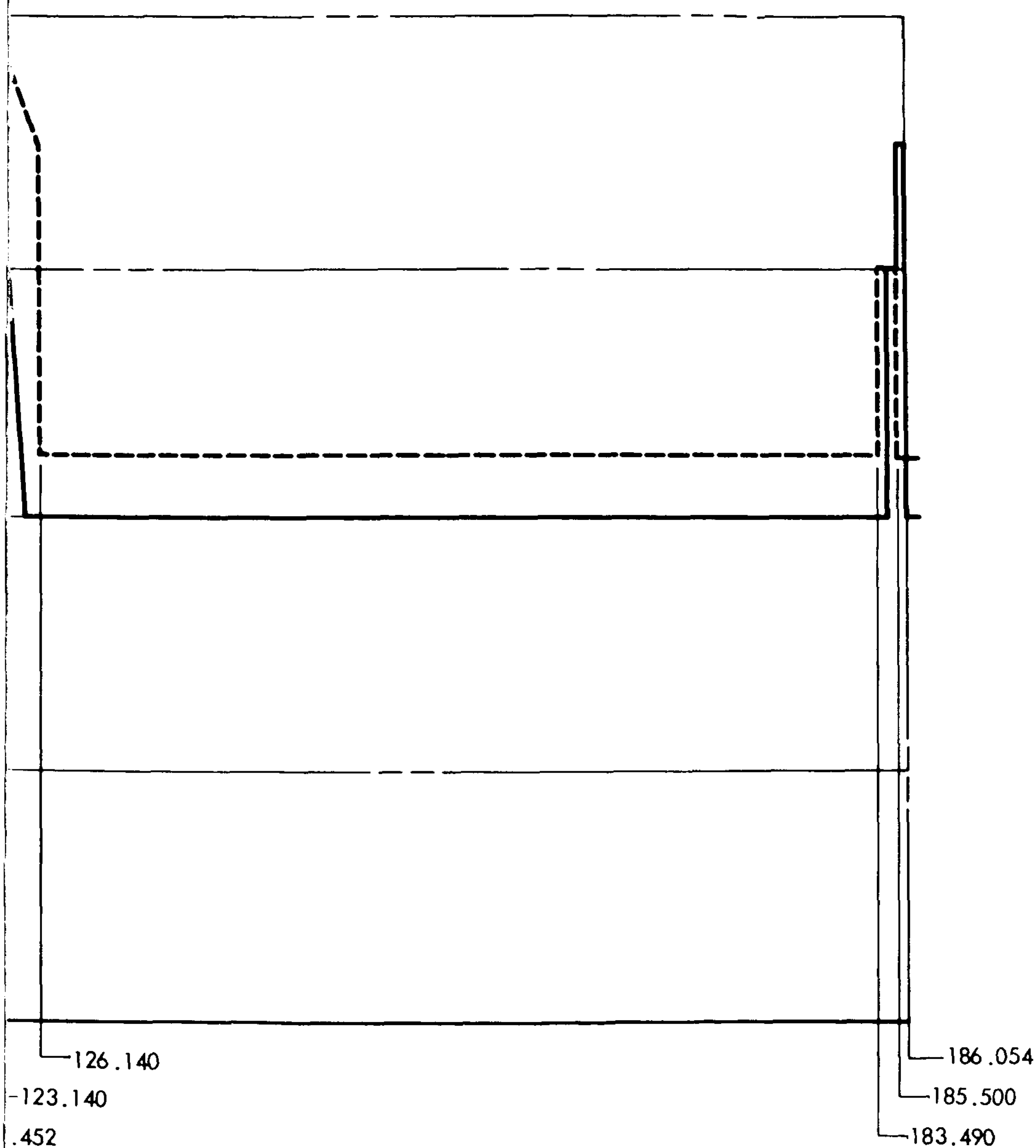



Figure 4. Crew Stress Load —Direct Flight Mission



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# Table 5. Crew Function Reliability - Lunar Orbital Rendezvous Mission

| Crew Function | Spacecraft Function | Phase | Man's Reliability |
|---|---|---|---|
| 1. Back up launch escape tower jettison<br>a. Monitor jettison status<br>b. Activate jettison backup | 6 | 1-2 | 0.99999 |
| 2. Back up electric-power inversion<br>a. Monitor inversion status | 7 | 1-18 | 0.9955 |
| b. Activate alternate inverter backup | 80<br>81<br>82 | 19-22<br>24-29<br>30-40 | 0.9991<br>0.9855<br>0.9869 |
| 3. Electrical power system management<br>a. Monitor electrical power system | 8P, A1-3 | 1-18 | 0.9999 |
| b. Activate alternate fuel cells | 83 A1-3 | 19-24 | 0.9955 |
| 4. Electrical power system management<br>a. Monitor electrical power system<br>b. Deactivate nonessential power consuming systems<br>c. Activate alternate fuel cells | 9P, A1-6 | 25-39 | 0.9927 |
| 5. Electrical power system change-over<br>a. Monitor electrical power system change-over<br>b. Activate alternate power sources | 10 | 40-41 | 0.9999 |
| 6. Check S/M reaction control system storage<br>a. Activate S/M reaction control system read-out<br>b. Check S/M reaction control system storage | 11 | 1-2 | 0.9971 |
| 7. Attitude control-manual<br>a. Maintain attitude control<br>b. Monitor guidance and navigation system<br>c. Check attitude displays<br>d. Check reaction control system tank quantity | 12 | 3-7 | 0.9940 |
| 8. Attitude control-manual<br>Same as No. 7. | 13P | 8-24 | 0.9939 |
| 9. Attitude control-manual and reaction control system management<br>a. Maintain attitude control<br>b. Monitor guidance and navigation system<br>c. Deactivate reaction control system tanks<br>d. Check remaining reaction control system supply<br>e. Check attitude display | 13 A1-6 | 8-24 | 0.9936 |
| 10. Attitude control-manual<br>Same as No. 7 | 14P | 25-39 | 0.9773 |
| 11. Same as No. 9 | 14 A1-10 | 25-39 | 0.9773 |
| 12. Check C/M reaction control system storage<br>a. Activate C/M reaction control system read-out | 15 | 1-24 | 0.9971 |
| b. Check C/M reaction control system storage | 84 | 25-41 | 0.9799 |

| Crew Function | Spacecraft Function | Phase | Man's Reliability |
|---|---|---|---|
| 29. Guidance and navigation monitoring – LEM | 27, 28 | 19 | 0.9999 |
| 30. Attitude control – LEM<br>a. Check attitude<br>b. Control attitude | 27, 28 | 19 | 0.9955 |
| 31. Attitude control – LEM<br>a. Check attitude<br>b. Control attitude | 89, 93 | 20 | 0.9955 |
| 32. Propulsion and attitude control – LEM<br>a. Initiate control engine ignition<br>b. Check engine status<br>c. Monitor velocity and range | 90, 94 | 21 | 0.9951 |
| 33. Propulsion and attitude control – LEM<br>a. Control engine<br>b. Check attitude<br>c. Monitor velocity and range<br>d. Manual attitude control | 91, 95 | 22 | 0.9879 |
| e. Deactivate propulsion system | 96 | | |
| 34. Launch – LEM<br>a. Monitor relevant displays<br>b. Initiate launch | 92, 96 | 27 | 0.9999 |
| 35. Rendezvous, not dock<br>a. Attitude control<br>b. Monitor range<br>c. Communication – LEM and C/M | 96 and 92 | 28 | 0.9999 |
| 36. Activate and regulate LEM environmental control system<br>a. Manual switching and activation<br>b. Back up automatic regulation | 29 | 18, 19, 20, 21, 22 | 0.9955 |
| 37. Activate and regulate LEM environmental control system<br>a. Manual switching<br>b. Back up automatic regulation<br>c. Utilize backpack<br>d. Pressurization adjustment | 30 | 23, 24 | 0.9955 |
| 38. Activate and regulate LEM environmental control system<br>a. Manual switching<br>b. Back up automatic regulation<br>c. Utilize backpack<br>d. Pressurization adjustment | 31P | 25, 26 | 0.9955 |
| 39. Backpack substitution<br>a. Utilize backpack<br>b. Deactivate LEM oxygen regulation | 31 A1-2 | 25, 26 | 0.9955 |
| 40. LEM environmental control system regulation<br>a. Monitor environmental control system | 32P | 27, 28, 29 | 0.9955 |

| | | | |
|---|---|---|---|
| 13. Same as No. 6 | 16<br>85 | 9-24<br>25-49 | 0.9971<br>0.9799 |
| 14. Entry flight control<br>a. Monitor guidance and navigation system<br>b. Manual back up of automatic control<br>c. Monitor attitude displays<br>d. Monitor reaction control system<br>e. Activate transfer valves<br>f. Deactivate engines as needed | 17P, A1-8 | 40-41 | 0.9835 |
| 15. Check S/M propellants<br>a. Activate S/M propellants readouts | 18 | 1-24 | 0.9971 |
| b. Check S/M propellants display | 86 | 25-38 | 0.9799 |
| 16. Monitor S/M propellants<br>a. Monitor S/M propulsion system panel<br>b. Monitor guidance and navigation system | 19 | 6, 8, 11, 13, 15, 16, 27, 30, 31, 32, 34, 36, 38 | 0.9999 |
| 17. Initiate separation S/M-C/M<br>a. Initiate S/M release<br>b. Confirm separation | 20 | 39 | 0.9999 |
| 18. Initiate and confirm earth landing system activation<br>a. Initiate or back up activation of subsystems (drogue chute, impact, attenuation, etc)<br>b. Confirm activation<br>c. Check altitude | 21 | 41 | 0.9899 |
| 19. Initiate and confirm main chute deployment<br>a. Check altitude<br>b. Initiate main chute deployment<br>c. Confirm | 22 | 41 | 0.9999 |
| 20. Regulate environmental control system<br>a. Monitor environmental control system displays | | | |
| b. Regulate environmental control system | 23 | 1-38 | 0.9999 |
| 21. Initiate earth entry environmental control system<br>a. Switch to C/M environmental control system<br>b. Monitor environmental control system displays<br>c. Back up automatic environmental control | 24P | 39-41 | 0.9927 |
| 22. Backpack utilization<br>a. Monitor environmental control system status<br>b. Switch to backpack | 24 A1-2 | 39-41 | 0.9999 |
| 23. Initiate LEM adapter jettison<br>a. Initiate jettison<br>b. Confirm jettison | 25 | 5 | 0.99999 |
| 24. Initiate and control transfer docking<br>a. Control attitude<br>b. Check LEM position<br>c. Control closure<br>d. Activate locking devices | 26 | 51 | 0.9955 |
| 25. Enter LEM<br>a. Don pressure suit<br>b. Pressurize hatch interlock<br>c. Open C/M and LEM hatch<br>d. Transfer to LEM | 87 | 18 | 0.9999 |
| 26. Systems check-LEM<br>a. Manual switching and checkout | 87 | 18 | 0.9953 |
| 27. Separation control<br>a. Release C/M-S/M locking devices<br>b. Initiate separation<br>c. Verify separation | 87 | 18 | 0.9999 |
| 28. C/M and LEM flight control docking<br>a. Attitude control<br>b. Communication – LEM and C/M<br>c. Visual observation – LEM and C/M<br>d. Control closing rates<br>e. Make contact<br>f. Secure contact | 88 | 29 | 0.9819 |

| | | | |
|---|---|---|---|
| b. Back up automatic regulation | | | |
| 41. Backpack substitution<br>a. Utilize backpack<br>b. Deactivate oxygen regulation | 32 A1-2 | 27, 28, 29 | 0.9955 |
| 42. Back up LEM landing gear jettison<br>a. Check LEM landing gear status<br>b. Back up jettison<br>c. Confirm jettison | 33 | 27 | 0.9999 |
| 43. Determine telecommunication status<br>a. Check telecommunication display<br>b. Activate system | 34 | 18, 29 | 0.9999 |
| 44. Monitor altitude<br>a. Monitor radar altimeter display | 35 | 19, 20, 21, 22, 27, 28 | 0.9988 |
| 45. Control LEM electrical power system<br>a. Monitor electrical power system<br>b. Switching | 36 | 18 through 29 | 0.9865 |
| 46. Attitude control – LEM<br>a. Check attitude<br>b. Control attitude | 37 | 19, 20, 21 | 0.9955 |
| 47. Propulsion and attitude control<br>a. Control engine<br>b. Check attitude | 37 | 22 | 0.9879 |
| 48. Launch – LEM<br>a. Monitor relevant displays | 37 | 27 | 0.9999 |
| 49. Rendezvous, not dock<br>a. Attitude control<br>b. Monitor range | 37 | 28 | 0.9999 |
| 50. LEM dock<br>a. Attitude control<br>b. Visual observation<br>c. Control closing rates<br>d. Make contact | 97 | 29 | 0.9819 |
| 51. LEM guidance and navigation<br>a. Monitor<br>b. Obtain read-outs | 38 | 18, 19, 20, 21, 22, 27, 28 | 0.9999 |
| 52. Guidance and navigation<br>a. Monitor guidance and navigation displays<br>b. Computer operations<br>c. Guidance and navigation systems checks | 50 | 3, 4 | 0.9953 |
| 53. Attitude control for LEM transfer<br>a. Check flight direction angle indicator<br>b. Control attitude | 98 | 5 | 0.9955 |
| 54. Navigation fixes<br>a. Select data<br>b. Star sightings<br>c. Enter data in computer<br>d. Set up attitude controls<br>e. Request computer read-outs | 51 | 6, 8, 11, 13, 15, 16, 24 | 0.9999 |
| 55. Alternative rendezvous and docking techniques<br>a. Attitude control<br>b. Monitor range<br>c. Monitor closure rates<br>d. Make contact<br>e. Lock | 52P, A1-10 | 28, 29 | 0.9815 |
| 56. Alternate transearth navigation fix techniques<br>a. Select data<br>b. Star sightings<br>c. Enter data in computer<br>d. Set up attitude controls<br>e. Request read-outs | 53P, A1-9 | 30, 32, 34, 36, 38 | 0.9997 |
| 57. Alternative entry for navigation and guidance and stabilization and control techniques<br>a. Guidance and navigation monitor<br>b. Attitude control<br>c. Monitor flight path<br>d. Deactivate engines as needed | 54P, A1-10 | 40, 41 | 0.9821 |



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| Cr |
| --- |
| 1. Back up launch esc<br>a. Monitor jettison<br>b. Activate jettiso |
| 2. Back up electric p<br>a. Monitor inversi<br>b. Activate alterna |
| 3. Electrical power s<br>a. Monitor electri<br>b. Activate alterna |
| 4. Electrical power s<br>a. Monitor electric<br>b. Deactivate none<br>systems<br>c. Activate altern |
| 5. Electrical power s<br>a. Monitor electric<br>change-over<br>b. Activate altern |
| 6. Check S/M reactio<br>a. Activate S/M re<br>read-out<br>b. Check S/M reac |
| 7. Attitude control –<br>a. Maintain attitud<br>b. Monitor guidan<br>c. Check attitude<br>d. Check reaction<br>quantity |
| 8. Attitude control –<br>Same as No. 7 |
| 9. Attitude control –<br>system managem<br>a. Maintain attitu<br>b. Monitor guidan<br>c. Deactivate reac<br>d. Check remainin<br>supply<br>e. Check attitude |
| 10. Attitude control–r<br>Same as No. 7 |
| 11. Same as No. 9 |
| 12. Check C/M reacti<br>a. Activate C/M<br>read-out<br>b. Check C/M r |
| 13. Same as No. 12 |
| 14. Entry flight cont<br>a. Monitor guida<br>b. Manual back u<br>c. Monitor attit<br>d. Monitor C/M<br>e. Activate tran<br>f. Deactivate en |
| 15. Check S/M prop<br>a. Activate S/M<br>b. Check S/M pr |
| 16. Monitor S/M pro<br>a. Monitor S/M<br>b. Monitor guida |
| 17. Initiate separatio<br>a. Initiate S/M r<br>b. Confirm separ |
| 18. Initiate and confi<br>activation<br>a. Initiate or ba<br>(drogue chute<br>b. Confirm activa<br>c. Check altitude |

# Table 6. Crew Function Reliability - Direct Flight Mission

| ew Function | Spacecraft Function | Phase | Man's Reliability |
|---|---|---|---|
| ape tower jettison | 6 | 1-2 | 0.99999 |
| a status | | | |
| n backup | | | |
| ower inversion | 7 | 1-16 | 0.9955 |
| ion status | | | |
| ite inverter backup | 80 | 17-19 | 0.9991 |
| | 81 | 22 | 0.9855 |
| | 82 | 23-34 | 0.9869 |
| ystem management | 8P, A1-3 | 1-16 | 0.9999 |
| cal power system | | | |
| ite fuel cells | 83 | 17-19 | 0.9955 |
| ystem management | 9P, A1-6 | 22-32 | 0.9935 |
| :al power system | | | |
| essential power-consuming | | | |
| ite fuel cells | | | |
| ystem change-over | 10 | 33-34 | 0.9999 |
| :al power system | | | |
| te power sources | | | |
| n control system storage | 11 | 1-2 | 0.9971 |
| action control system | | | |
| tion control system storage | | | |
| manual | 12 | 3-7 | 0.9940 |
| e control | | | |
| e and navigation system | | | |
| splays | | | |
| ontrol system tank | | | |
| anual | 13P | 8-20 | 0.9939 |
| anual and reaction control | 13 A1-4 | 8-20 | 0.9936 |
| control | | | |
| e and navigation system | | | |
| tion control system tanks | | | |
| reaction control system | | | |
| splays | | | |
| anual | 14P | 21-32 | 0.9779 |
| | 14 A1-10 | 21-32 | 0.9779 |
| n control system storage | 15 | 1-19 | 0.9971 |
| action control system | | | |
| ion control system storage | 84 | 21-34 | 0.9799 |
| | 16 | 2-19 | 0.9971 |
| | 85 | | 0.9799 |
| | 17P, A1-8 | 33-34 | 0.9835 |
| and navigation system | | | |
| f automatic control | | | |
| isplays | | | |
| ction control system | | | |
| valves | | | |
| s as needed | | | |
| ts | 18 | 1-19 | 0.9971 |
| pellants read-out | | | |
| llants display | 86 | 22-31 | 0.9799 |
| lants | | | |
| pellants system panel | 19 | 22, 23, 24, 25 27, 29, 31 | 0.9999 |
| and navigation system | | | |
| /M and S/M | 20 | 32 | 0.9999 |
| ase | | | |
| ion | | | |
| earth landing system | 21 | 34 | 0.9899 |
| p activation of subsystems | | | |
| mpact attenuation, etc.) | | | |
| ion | | | |

| Crew Function | Spacecraft Function | Phase | Man's Reliability |
|---|---|---|---|
| 19. Initiate and confirm main chute deployment<br>a. Check altitude<br>b. Initiate main chute deployment<br>c. Confirm | 22 | 34 | 0.9999 |
| 20. Regulate environmental control system<br>a. Monitor environmental control system displays<br>b. Regulate environmental control system | 23 | 1-19, 22-31 | 0.9999 |
| 21. Initiate earth entry environmental control system<br>a. Switch to C/M environmental control system<br>b. Monitor environmental control system displays<br>c. Back up automatic environmental control | 24P | 32, 33, 34 | 0.9929 |
| 22. Backpack utilization<br>a. Monitor environmental control system status<br>b. Switch to backpack | 24 A1-2 | 32, 33, 34 | 0.9999 |
| 23. Activate and regulate environmental control system<br>a. Manual switching and activation<br>b. Back up automatic regulation | 25 | 20 | 0.9955 |
| 24. Activate and regulate environmental control system<br>a. Manual switching<br>b. Back up automatic regulation<br>c. Utilize backpack<br>d. Pressurization adjustment | 26P | 21 | 0.9959 |
| 25. Backpack utilization<br>a. Utilize backpack<br>b. Deactivate C/M oxygen regulation | 26 A1-2 | 21 | 0.9959 |
| 26. LLM propulsion control and management<br>a. Navigation fixes<br>b. IMU alignment<br>c. Propulsion activation and deactivation | 27 | 5, 7, 10, 12 | 0.9999 |
| 27. Monitor, activate, confirm<br>a. Monitor velocity and range<br>b. Monitor map display<br>c. Manually control propulsion<br>d. Confirm touch-down | 28 | 19 | 0.9846 |
| 28. Initiate and confirm LLM separation, guidance and navigation | 29 | 22 | 0.9999 |
| a. Monitor guidance and navigation displays<br>b. Computer operations<br>c. Guidance and navigation systems checks | 30 | 3, 4 | 0.9953 |
| 29. Navigation and guidance stabilization and control<br>a. Navigation fixes<br>b. IMU alignment<br>c. Automatic and manual back up stabilization and control, propulsion<br>d. Computer operations | 31 | 5, 7, 10, 12, 14, 15, 16 | 0.9999 |
| 30. Alternate navigation and guidance — lunar landing and launch<br>a. Monitor velocity and range<br>b. Monitor map display<br>c. Initiate and deactivate propulsion<br>d. Manual back up of attitude control and propulsion control<br>e. Computer read-outs | 32P, A1-8 | 17, 18, 19, 22 | 0.9955 |
| 31. Alternate transearth navigation fix techniques<br>a. Select data<br>b. Star sightings<br>c. Enter data in computer<br>d. Set up attitude controls<br>e. Request read-outs | 33P, A1-8 | 23, 24, 25, 27 29, 31 | 0.9997 |
| 32. Alternative entry navigation and guidance and stabilization and control techniques<br>a. Guidance and navigation monitor<br>b. Attitude control<br>c. Monitor flight path<br>d. Deactivate engines, as needed | 34P, A1-10 | 23, 33, 34 | 0.9821 |



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The crew function reliability estimates shown in Tables 5 and 6 generally reflect three main considerations.

1. The intrinsic difficulty of the crew functions as indicated by the rating of the standard tasks to which they corresponded

2. The time for performance stress under which the functions were conducted

3. The additional effect of fatigue upon conditions 1 and 2 above

The effect of subjective evaluation of these considerations is shown in the tendency for crew function reliabilities to be higher for functions occurring in the outbound mission phases than those functions occurring during the inbound phases, when fatigue is greatest. The lowest reliabilities reflect situations of time limits and fatigue. These situations occur notably during lunar-orbital docking. Crew function reliabilities during the inbound mission phases tend to be somewhat higher for the DF than the LOR mission, as it was felt that the LOR mission crew performance would reflect the stress of the one-man lunar orbit and the docking phase.

Some crew functions were considered as exceptions to the general treatment just described. These included simple tasks that would not be affected by fatigue or time pressure and, occasionally, such tasks where it was felt that over-compensation could be expected to maintain performance reliability in the face of fatigue.

## 2.3 SUPPLEMENTARY CONSIDERATIONS

The reliability values presented were based upon consideration of task difficulty under several assumed task conditions. A number of additional factors also may effect crew function reliability. However, these factors are not amenable to immediate reduction to quantitative terms. More significant factors are:

1. Crew work load considerations

2. Display panel design characteristics

3. C/M cabin space utilization

4. Visual aspects of lunar landing

5. Physiological stress



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The possible significance of these factors on either mission is discussed in the paragraphs that follow. The objective of this analysis was to identify potential sources of unreliability not directly reflected in the procedure for estimating crew function reliabilities as presented in the previous section. It should be noted, however, that factors such as task loading, stress, fatigue, etc., received weighted consideration in the numerical estimates presented. Weighted considerations also were applied in terms of the lower limits for the distribution of standard tasks reliability. A three- versus a two-man DF mission also is briefly considered. A summary comparison of the LOR and DF missions relative to these factors is presented at the conclusion of this section.

### 2.3.1 Crew Work Load Considerations

Demonstration of a significant difference in crew work-load requirements in relation to LOR and DF operations and assignment of tasks would serve to show points of crew overload in either the LOR or DF mission. For this reason, an analysis was made of the crew work load for each crew member for the three-man LOR and two-man DF missions. The analyses included consideration of time for operator in-flight duties and time available for maintenance tasks.

Crew work loads represent the percentage of time that each crew member is occupied by inflight duties directly related to the operation of the Apollo spacecraft and the LEM. The workload data have been presented in Figures 1 and 2.

Material from previous DF and LOR mission studies of crew functions was utilized to analyze the individual crew member tasks. On the basis of the investigator's familiarity with the Apollo systems and crew functions, including previous time-line analysis results, performance times were assigned to each task for each crew member. For the two-man, DF mission, the tasks and task times that were assigned to the SM (systems manager) in the LOR mission were distributed between the PC (pilot commander) and CP (copilot). For most phases, the phase time was divided into the total phase task time for each crew member. This yielded the percentage workload figures. The phases in which this procedure was departed from were the one-man (CP) orbit – from the time the LEM separates for lunar landing until the beginning of docking – and translunar and transearth coast phases.

In establishing workloads for the one-man, spacecraft orbit during the lunar landing and exploration phases, it was assumed that the CP would be largely concerned with guidance and navigation, stabilization and control, monitoring and systems check, and communication functions. However, it was also considered that he could not do this for 24 or 48 hours without some



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provision for rest, personal hygiene, and eating. Therefore, the CP was given 54 minutes of free time during the latter part of every third orbit. The workload for the translunar and transearth coast phases was computed on the basis of one man being continuously on watch station. The time was shared equally, i.e., one-third of the time for each man of a three-man crew and one-half of the time for each man of a two-man crew. Added to this watch station workload was a similar division of navigation fix time. The phase time base for the coast phases was the total time for the phases considered, i.e., for LOR phases 7 to 14 and 33 to 37 and for DF phases 6 to 13 and 26 to 30.

Figures 1 and 2 also show the percentage of time available for maintenance by selected crew members after normal duty time and time for rest, personal hygiene, eating, etc. With the exception of the translunar and transearth coast phases, the crew member available for maintenance was considered to be the least occupied man for the LOR mission and the most occupied man during the DF mission. The reason for the difference is that during the LOR mission the least occupied crew member is most available; while in the DF mission, the least occupied crew member cannot leave his duty station until the most occupied crew member can substitute for him. No maintenance time availability is shown unless the specified crew member's occupied time, subtracted from total phase time, leaves sufficient time for him to perform at least one maintenance action. A maintenance action consists of a cycle of activities including malfunction isolation, obtaining a replacement module, going to the locus of the malfunction, and replacing the malfunctioning module. It is estimated that a crew member in shirt sleeves should take no more than 30 minutes to perform a maintenance cycle.

Table 7 summarizes the data for inflight maintenance. In computing the number of maintenance cycles possible in a phase, the percentage of time occupied for the selected crewman was taken from Figures 1 and 2, and subtracted from 100-percent phase time. The resulting percent of "free" time was converted into hours. The standard maintenance cycle time (0.500 hour) was divided into the free time to obtain the number of maintenance cycles possible for the phase. This procedure is based on the assumption that the crew member's free time will not be so broken up as to interfere with a 30-minute maintenance cycle.

The somewhat different approaches to workload calculation, i.e., task time and distributed phase time, yield corresponding differences in the significance of workload figures. Where task times form the basis for workload, the percentages reflect the estimated time that the crew member actually is occupied; where distributed phase time is used, i.e., in coast phases the crew members duty time is given, but there is no reflection of how busy he actually is.

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Table 7. Summary Data for In-Flight Maintenance

| Lunar Orbital Rendezvous Mission | | | Direct Flight Mission | | |
|---|---|---|---|---|---|
| Phase | Maintenance | Remarks | Phase | Maintenance | Remarks |
| 1 | No | Insufficient time, immobilized crew | 1 | No | Insufficient time, immobilized crew |
| 2 | No | Insufficient time, immobilized crew | 2 | No | Insufficient time, immobilized crew |
| 3 | Yes | Two maintenance actions,* one may interfere with CP in lower equipment bay | 3 | Yes | One maintenance action |
| 4 | No | Insufficient time, immobilized crew | 4 | No | Insufficient time, immobilized crew |
| 5 | No | Insufficient time, immobilized crew | | | |
| 6 | Yes | Five maintenance actions, may interfere with CP in lower equipment bay | 5 | No | CP in lower equipment bay at all times |
| 7-14 | Yes | Limited in location by periodic occupation of lower equipment bay for first two hours and last four hours - One man available at all times | 6-13 | Yes | Between first two hours and last four hours with varying interference with rest portion of work/rest cycle |

| | | | | | |
|---|---|---|---|---|---|
| 15 | Yes | Five maintenance actions, two of which may interfere with CP in lower equipment bay | 14 | Yes | Three maintenance actions |
| 16 | No | Insufficient time, immobilized crew | 15 | No | Insufficient time, immobilized crew |
| 17 | Yes | Three maintenance actions | 16 | Yes | One maintenance action |
| 18 | Yes | Five maintenance actions for C/M and LEM | 17** | No | Insufficient time, immobilized crew |
| 19 | No | Insufficient time, immobilized crew | 18** | No | Insufficient time, immobilized crew |
| 20 | No | Insufficient time, immobilized crew | 19** | No | Insufficient time, immobilized crew |
| 21 | No | Insufficient time, immobilized crew | | | |
| 22 | No | Insufficient time, immobilized crew | | | |
| 23 | Yes | At expense of scientific duties | 20 | Yes | At expense of scientific operations |
| 24 | | | | | |
| 25 | Yes | Unknown amount | 21 | Yes | Unknown amount |
| 26 | | | | | |
| CP Lunar Orbit | Minimal | Only if critical to crew safety | | | |
| 27 | No | Insufficient time, immobilized crew | 22 | No | Insufficient time, immobilized crew |
| 28 | No | Insufficient time, immobilized crew | | | |

| | | | | | |
|---|---|---|---|---|---|
| 29 | No | Insufficient time | | | |
| 30 | Yes | Two maintenance actions, one of which may interfere with CP in lower equipment bay | 23 | Yes | Two maintenance actions |
| 31 | No | Insufficient time, immobilized crew | 24 | No | Insufficient time, immobilized crew |
| 32 | Yes | Four maintenance actions, may interfere with CP in lower equipment bay | 25 | No | CP in lower equipment bay at all times |
| 33-37 | Yes | Limited in location by periodic occupation of lower equipment bay for first hour and last four hours - One man available at all times | 26-30 | Yes | Between first hour and last four hours with varying interference with rest portion of work/rest cycle |
| 38 | | Four maintenance actions, may interfere with CP in lower equipment bay | 31 | Yes | One maintenance action, final part of phase |
| 39-40-41 | No | Insufficient time, immobilized crew | 32-33-34 | No | Insufficient time, immobilized crew |

*Maintenance action consists of malfunction isolation, obtaining replacement module, going to malfunction, and replacing module.
**Do not correspond to LOR phases.



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The workload for the phases where task times were the computational basis is probably understated by the percentages in some phases. Part of this understatement derives from the difficulty of allotting task time to monitoring activities. However, the critical question here is whether or not the crew member has adequate time to carry out the necessary tasks. The present workload analysis does not indicate any categories where the time allowed for task performance is clearly inadequate.

The workload for the phases (translunar and transearth coast), where distributed phase time rather than actual time is shown, is probably fairly well estimated by the percentages presented, unless an extremely heavy burden of maintenance occurs in addition to watch station and navigation duties. The nominal distribution of crew workload for the coast phases of both the LOR and DF missions is summarized in Table 8.

On the basis of the crew work load analyses, it may be concluded that adequate time is available for all crew operations in terms of total phase time. This does not mean that the time available for a given operation at a certain period within a phase is necessarily adequate.

The analyses tend to support the assumption that, for both the LOR and the DF missions, at least a minimum of adequate time will be available during translunar coast phases for sufficient rest, personal hygiene, eating, etc. This time is necessary to maintain the crew members in condition for required operations. It is felt, however, that the crew of the DF mission will be somewhat less fatigued than that of the LOR mission, since they will not have been exposed to the stress of the one-man orbital flight and lunar orbital docking operations of the LOR mission.

The time available for maintenance would seem to be adequate for a relatively large number of modular replacement maintenance cycles by the "least available" crew member (i.e., either the PC or CP in the DF mission) without interfering with watch station and navigation duties or diminishing the amount of time allocated to rest, personal hygiene, eating, etc. There is, of course, the possibility that maintenance requirements might somewhat disrupt any schedule of work-rest cycles.

In addition to the workload data shown in Figures 1 and 2, additional information on stress loading is given in Figures 3 and 4 for the LOR and DF missions. The ordinate of Figures 3 and 4 represents essentially the conditions of time, pressure, and fatigue which are described in section 2.1. and involve the assumption that these conditions are present linear increments of stress. These data represent a subjective judgment of stress loading at various times during the mission.

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Table 8. Crew Workload Summary—Coast Phases

| Crew Function | Lunar Orbital Rendezvous Mission | | | | Direct Flight Mission | | |
|---|---|---|---|---|---|---|---|
| | Phase | Pilot Commander (Hr) | Copilot (Hr) | Systems Manager (Hr) | Phase | Pilot Commander (Hr) | Copilot (Hr) |
| Watch station and navigation | 7-14 | 22 | 23 | 22 | 6-13 | 32 | 33 |
| Rest, personal hygiene, eating, etc. | 7-14 | 21 | 21 | 21 | 6-13 | 21 | 21 |
| Maintenance | 7-14 | 20 | 19 | 20 | 6-13 | 11 | 10 |
| Phase total (translunar coast) | 7-14 | 63 | 63 | 63 | 6-13 | 64 | 64 |
| Watch station and navigation | 33-37 | 19 | 20 | 19 | 26-30 | 29 | 29 |
| Rest, personal hygiene, eating, etc. | 33-37 | 19 | 19 | 19 | 26-30 | 19 | 19 |
| Maintenance | 33-37 | 19 | 18 | 19 | 26-30 | 8 | 8 |
| Phase total (transearth coast) | 33-37 | 57 | 57 | 57 | 26-30 | 57 | 57 |

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### 2.3.2 Display Panel Design

The design of a display panel for two crew members must incorporate all of the essential displays which are currently organized for the three Apollo crew members. (Panel design considerations discussed herein are limited to the main display panel, inasmuch as displays located in the lower equipment bay are designed for one-man utilization.)

On the basis of the task analysis which was carried out for crew workload, a link analysis was completed for phases of the three-man LOR mission which corresponded to the two-man DF mission. The link analysis utilized drawings of the Apollo three-man display panel and identified the displays which each crew member utilized most frequently. This information was utilized to re-group for two-man utilization the displays in the three-man layout. No attempt has been made to develop a formal display panel design because such an end-product would entail more extensive effort than this study permitted. Rather, the present approach is to re-group the three-man panel displays to indicate a possible organization of displayed information for a two-man system. The PC was provided primarily with accessible information most pertinent to his role as pilot, plus a few displays assigned as his primary responsibility as a crew member. The CP was assigned displays for which he is primarily responsible as a crew member. The displays do not reflect the CP's speciality as a navigator, since most of his navigation displays are not on the main display panel. Remaining displays were assigned to a "common" category as being available to either PC or CP on an ad hoc basis. This distribution is applicable to mission phases or phase segments when both the PC and CP are at the display panel. The display distribution does not take into account the possibilities of individual display redesign in organizing a two-man display panel.

While there is no single standard way to organize the two-man display panel, the general principle of such an organization would seem to be to group displays for which a given crew member is individually responsible on the crewman's side of the panel and to place "common" displays in the center within the "overlap" of crewmen's visual fields. Although the preceding organization of a two-man display panel is not presented as definitive, it does indicate that a three-man display can be reorganized to meet the requirements of two crew members. This result is not surprising because Apollo display panel has been designed with three considerations in mind. First, it is basically a panel for two-man (i.e., command pilot and copilot) operation. Second, the panel is to be monitored during most of the transit to the moon and returned by one crewman. Third, the C/M can be returned to earth by one crewman. All these factors favor redesign of the panel for a two-man crew.

The illustrative distribution of displays (and associated controls) which resulted from the procedure described above is shown in Figure 5.

Since analysis of display requirements and display utilization indicates that the three-man display of the LOR mission can be reorganized to meet the requirements of two crew members, it appears that no effect of display organization on crew functional reliability need be attributed to either a three-man or two-man mission mode on a comparison basis.

### 2.3.3 C/M Cabin Space Utilization

Space availability for performing in-flight operations may have a significant effect on mission crew functional reliability. To assess the space availability factor, a comparison was made of a three-man C/M layout and a two-man C/M layout in reference to in-flight operations, including watch-keeping, main display panel activities, navigation, and sleeping. Maintenance activities were not considered, since the locations for modular replacements were not known.

Drawings showing interior volumes for the two-man and three-man C/M, respectively, were utilized to obtain clearance data. These drawings showed the 90th-percentile crewman at selected locations and body positions in the C/M. These standard locations were considered for both two- and three-man C/Ms:

a. The main display panel

b. Lower and upper equipment bays

c. Sleeping locations

At each location, least and greatest clearances between the crew member and his surroundings were measured on the drawings noted above. These clearances, shown in Table 9, apply to a 90th-percentile crewman in a pressurized suit. Selected locations account for a majority of inflight duties. The main display panel location covers watch keeping and "powered flight" phases while the lower and upper equipment bay covers navigation fixes and certain controls and displays.

Both command modules seem to offer approximately equal clearances to the main display panel. The three-man C/M seems to offer greater clearances at lower and upper equipment bay locations. It was assumed that the two-man C/M could sleep one man, semi-reclining, essentially at the main display panel location. The sleeping crew member would have more horizontal clearance than allowed in the three-man sleeping location.

[redacted]

| PILOT-COMMANDER DISPLAYS | DISPLAYS COMMON TO PILOT-COMMANDER AND COPILOT | COPILOT DISPLAYS |
|---|---|---|
| STABILIZATION AND CONTROL SYSTEM CONTROL | ABORT LIGHT | LIGHTING CONTROLS |
| ENTRY MONITORING INDICATOR | MASTER CAUTION LIGHTS | ENVIRONMENTAL CONTROL SYSTEM |
| INTEGRATED DISPLAY | BAROMETRIC INDICATOR | LIQUID DISPLAY |
| GIMBAL POSITION INDICATOR | ANTENNA CONTROL | ENVIRONMENTAL CONTROL SYSTEM |
| S IVB RESTART | CRYOGENIC | GAS DISPLAY |
| EMERGENCY CONTROLS | FUEL CELL | BOOSTER SITUATION INDICATOR |
| AUDIO CONTROL | POWER DISTRIBUTION 1, 2, AND 3 | STABILIZATION AND CONTROL SYSTEM |
| COMPUTER KEYBOARD AND READOUT | IN-FLIGHT TEST SYSTEM SWITCH | POWER CONTROL |
| FLIGHT DIRECTION ATTITUDE INDICATOR | CLOCK TIME INDICATORS | SM QUADRANT TEMPERATURE INDICATOR |
| | | SERVICE PROPULSION |
| | | AUDIO CONTROL |
| | | REACTION CONTROL |
| | | TELECOMMUNICATION CONTROL |

Figure 5. Distribution of Displays



[redacted]

[redacted]

Table 9. Command Module Crew Member Clearances

| Three-Man Lunar Orbital Rendezvous Mission | | | | Two-Man Direct Flight Mission | | | |
|---|---|---|---|---|---|---|---|
| Location | Crew Position | Least Clearance (In.) | Greatest Clearance (In.) | Location | Crew Position | Least Clearance (In.) | Greatest Clearance (In.) |
| Main display panel | Seated | 10 (vertical)* | 20 (horizontal) | Main display panel | Seated | 10 (vertical) | 20 (horizontal) |
| Lower and upper equipment bay | Standing (couch removed) | 14 (horizontal)** | 15 (vertical) | Lower and upper equipment bay | Standing (couch removed) | 8 (horizontal) | 10 (vertical) |
| Sleeping | Full length | 10 (vertical) | 4 (horizontal) | Sleeping | Full length | 8 (horizontal) | 10 (vertical) |

*Overhead clearance
**Clearance from front, back or side of body

[redacted]

The reduced clearance afforded by the two-man C/M in the lower equipment bay could be critical. Specialized training for working in a confined space must reduce this criticality to the point where navigational fix operations can be carried out efficiently enough not to degrade mission reliability.

The effects of the reduced volume of the DF C/M upon performance generally are difficult to determine without experimental data. A two-man confinement study, performed at Ames with a volume per man of approximately 60 ft.$^3$, showed no effects attributable to this relatively small volume. Volume, per se, is not relevant, provided it is sufficient to contain a crew. Layout of work space and duty stations, sleeping area, etc., is of primary importance. A volume of 80 ft.$^3$ appears adequate for two crewmen in the containment sense. The configurement of such a volume to provide a habitable environment is mainly a design problem.

It appears that adequate access for in-flight operations is available for both the LOR and DF missions, and crew function reliability need not be considered as degraded by inadequate access for either the LOR or DF mission. Adequacy of access for in-flight maintenance in the two-man C/M could not be determined, due to insufficient information on placement and dimensions of replacement modules, so this merits additional study.

### 2.3.4 Visual Aspects of Lunar Landing

Since the LEM is primarily a lunar landing vehicle and the C/M must, in addition to lunar landing, be designed for earth atmosphere entry, certain configurational characteristics can effect the line of sight of the crew members from the LEM and the CM to the lunar surface and, hence, the lunar landing operation.

The current Apollo C/M landing window could provide a 45-degree line-of-sight angle over the lower edge of the window, relative to the longitudinal axis of the C/M and to the line of vertical descent when the C/M longitudinal axis is parallel to this line of descent. A smaller C/M could increase this angle.

While the exact configuration of the LEM was not known at the time of this investigation, a study of possible configurations indicated that the line-of-sight angle should not be shallower than 30 degrees. This line-of-sight could afford a direct viewing of a larger area of lunar surface much closer to the descending spacecraft than can be viewed from the Apollo C/M, assuming both capsules descended vertically.

[redacted]

The adequacy of the view angle from either configuration, or the steps which might be taken to ameliorate the constraints imposed by the C/M and/or LEM configuration are beyond the scope of this study. However, optical aids (e.g., periscopes), canting the incoming landing craft, instruments (e.g., altimeters and/or electronic or nuclear markers), and intensive training could do much to improve the crew's efficiency in performing the lunar landing.

### 2.3.5 Three-Man Versus Two-Man DF

It is felt that a three-man DF mode would result in increased reliability over a two-man DF mode. However, the extent of this improvement would be difficult to estimate. There are justifications for the use of a three-man crew which have little to do with reliability in the usual sense.

The most important justification is in the availability of another crewman as a margin of safety in the event of the incapacitation of one or both of the other crew members. This may not significantly affect overall reliability as determined by typical analysis, but it may mean recovery of a crew and vehicle in the event of some contingency. In the case of manned vehicles, this is a worthwhile consideration.

There also is the obvious advantage of having another pair of hands and eyes during a "normal" mission. Observations can be taken and experiments performed which would not be possible with a two-man crew. In addition, the design of subsystems that can be made for a three-man crew affords greater feasibility and choice of alternatives.

With regard to reliability improvement, the greatest gain would be from increased redundancy of human operators considered as components (i.e., as sensors, computers, controllers, etc.). Whether this is worthwhile depends upon how effectively the increased capability is used in designing the system.

A second source of increased reliability is in the area of lunar operations. With a three-man crew, two men can explore the lunar surface together with surveillance by a third man in the capsule. With a two-man team, this would not be possible. Again, this is a matter of increased safety and extension of the system's capability in performing operations.

As noted, such considerations as these are difficult to reduce to numerical estimates of reliability. The net effect, however, should be an increase in reliability for a three-man mission over a two-man mission.



[redacted]

## 2.3.6 Physiological Stress

Although the environmental stresses imposed upon the crews of the DF and LOR modes are quite similar, there appear to be two main differences. First, in the LOR mode, two men are available for duty at all times; and, in the DF mode, this would be so only for a limited time each day. Secondly, the LOR mode requires additional stress for in-suit operations (e.g., during transposition, docking, crew transfer, separation, and rendezvous) than those required in the DF mode. The first difference results in a longer duty cycle for DF crews and reduces the opportunity for visual monitoring of crew status. The second presents stresses for LOR crews not encountered in the case of DF crews. These differences have not been considered weighty enough to favor one mode over another.

## 2.3.7 Summary

In summary, factors which are not readily amenable to quantification (but, nevertheless, may have a significant effect on crew function reliability) were compared for the LOR and DF missions. Conclusions regarding the significance of these factors are:

Crew Work Load

No significant task overloading occurs in either the LOR or the DF mission. In either mission mode, the crew would have:

1. At least enough time to perform routine operations

2. Sufficient time for rest during translunar and transearth coast phases

In-flight maintenance requirements were not considered, per se, but time and personnel availability were considered adequate for both the LOR and DF missions.

Display Panel Design

The DF mission display panel can be designed so that all essential display information will be presented to two crew members, and the data could be presented in such a manner that no effect on crew function reliability need be attributed to either the three-man LOR or the two-man DF mission.

[redacted]

C/M Cabin Space Utilization

In both the LOR and DF missions, adequate space could be made available to ensure crew access to all cabin areas essential to in-flight operations. Maintenance access was not considered due to lack of data concerning location characteristics of modular replacement maintenance.

Visual Aspects of Lunar Landing

The organization of spacecraft systems and crew functions under which reliability estimates were made did not permit direct consideration of C/M and LEM vehicle external configuration upon lunar hover and landing. Landing aids and intensive crew training would appear to be required for either mission.

Three-Man DF Mission

A three-man crew for the DF mission could enhance reliability by increasing redundancy and providing a back-up in the event of the incapacitation of one or more crew members. Other advantages include an increase in the possible number of observations and experiments, as well as increased scope and reliability of lunar operations.

Physiological Stress

No significant physiological effect upon reliability can be attributed to either mode. Some indication exists that there is a slight physiological advantage utilizing the DF mode.

## 3.0 RELIABILITY ANALYSIS

Although the basic hardware components for the two modes were assumed to be identical, insofar as possible, significant differences exist between these modes in the areas of human factors and hardware utilization. Specifically, one of the modes may require the crew to perform more difficult tasks after extended exposure to the stresses of space flight than does the other (e.g., rendezvous and docking functions required in the LOR mission). If so, the result could be a decrease in the probability of mission success and crew safety or both. It is the intent of this section to analyze and determine quantitatively the magnitude and significance of these differences.

Of fundamental importance to the manned lunar missions is the problem of assuring a high probability of mission success and crew safety. A successful mission requires that a very long sequence of events occurs exactly as planned with some controllable exceptions. Of prime importance is crew survival in the event of a mission failure.

To provide a realistic evaluation of mission success and crew safety for the LOR and two-man DF modes, the effect of man's capability to perform prescribed tasks will be presented concurrent with the mission phase profile.

### 3.1 GROUND RULES

Ground rules for the analysis were:

1. Current Apollo component failure rates wherever available were employed in this study.

2. A 24-hour planned stay on the moon was assumed with the capability of an additional 24-hour emergency stay.

3. Mission success was defined as performing planned mission operations with the number of primary and alternate modes required to meet the mission success requirements for all phases up to and including the 24-hour stay on the moon. Mission success for the remainder of the mission was considered to be synonomous with the crew safety definition (i.e., to include all primary and alternate modes of operation necessary for the safe return of the crew).

4. It would be possible to launch the two-man direct flight vehicle with the C-5 launch configuration.

[redacted]

5. Automatic control of the entire mission by GOSS was not considered because complete control would require additional equipment and impose an extreme weight penalty.

6. The functions of man in the two-man DF mission parallelled those functions of man in the LOR mission as much as was possible.

7. The reliability of man's performance was to be considered by mission phase or by function, depending upon the complexity of man's function within a given phase.

## 3.2 APPROACH

The approach was:

1. Establish detailed phases of both missions with respect to spacecraft functions.

2. Determine functions performed by man for:

   a. The two-man DF mission

   b. The three-man LOR mission

3. Generate numerical values representing the probability of man successfully performing each function.

4. Correlate the performance of man with the S/C hardware performance for each phase of the mission.

The complexity of man's functions and his relationship to the spacecraft hardware required that an analysis on the component and functional level of the spacecraft be made to properly correlate the performance of both man and hardware for each phase of the mission. Tables 3 and 4 describe the function-phase relationships. The utilization of such data to establish the reliability of man's performance has already been described.

A review of spacecraft hardware reliabilities in the NASA work statement (RFP 10-220) disclosed inadequate data for the proposed depth of analysis. Permission was requested and granted by NASA to employ Apollo spacecraft hardware data available in-house which appeared adequate to perform the required analysis. Apollo S/C hardware, using state-of-the-art failure rates were employed with the following exceptions:

a. The reliability of the three boosters

b. The reliability of the service module propulsion engines

c. The reliability of the lunar excursion module

Booster reliabilities were those in the work statement, inasmuch as complete in-house information concerning these reliabilities was not available. The service module propulsion engines reliability data used were apportioned values, since information was not available on propulsion engines utilizing cryogenic fuels. Inasmuch as the reliability used for the service module propulsion engine was the same for both the DF and LOR missions, there was no effect on comparative mission reliabilities.

Reliability values for the lunar excursion module were also apportioned values based on S&ID studies (S&ID 62-1040, "Apollo Preliminary Interface Specifications for LOR Mission"). Detailed information was not available on LEM hardware and, therefore, the system was configured from previous S&ID studies. Numerical reliability for man's performance previously developed were correlated with spacecraft hardware functions.

A logic diagram, which graphically represented the relationship of the working components (inclusive of man and the function in question), was developed for both the two-man DF and LOR missions. The effect of man's performance on the probability of mission success and crew safety for the two-man DF and LOR missions was obtained by comparing a "perfect" man ($R_{man} = 1$) and a "real" man ($R_{man} \leq 1$). To determine the effect of in-flight maintenance on two-man DF and LOR missions, spacecraft reliability logic diagrams, which both included and excluded in-flight maintenance, were developed. Thus, a total of eight configurations were analyzed for mission success reliability. In addition, three configurations were analyzed to determine crew safety probabilities. The eight mission configurations and the type of analysis considered, i.e., mission success (MS) or crew safety (CS), are summarized below:

| Conditions of Configurations | Two-Man DF Mission | LOR Mission |
|---|---|---|
| $R_{man} = 1$, w/o maintenance | MS | MS |
| $R_{man} = 1$, with maintenance | MS | MS |
| $R_{man} \leq 1$, w/o maintenance | MS and CS | MS |
| $R_{man} \leq 1$, with maintenance | MS and CS | MS and CS |

[redacted]

## 3.3 METHODOLOGY

### 3.3.1 Mission Success Probability

A mathematical reliability model, employing Monte Carlo techniques, has been developed for mission success reliability analysis on the Apollo program. This model, which is programmed for the IBM 7090, provided a most efficient and sophisticated tool for analyzing both mission success for the entire mission and crew safety for those phases of the mission where crew safety reliability can be considered synonomous with the mission success reliability (as described in the ground rules). Crew safety reliabilities for other phases of the mission are developed analytically and are described below.

Briefly, the Monte Carlo program solves the fundamental reliability equation, which (assuming an exponential failure rate) can be written in the following form:

$$R = e^{-\lambda_t t}$$

or

$$R = e^{-\lambda_c C}$$

where:

$R$ = reliability value at time $t$ $(0 \geq R \geq 1)$

$\lambda$ = failure rate

$t$ = mission time

$C$ = number of cycles

The computer program provides the capability to examine a large number of possible missions. In this study, some 5,000 missions were simulated on each configuration for each mode in order to obtain two-place accuracy in the final results.

The process selects times and/or cycles to failure from the time-to-failure and/or cycles-to-failure distributions for components with failure rates $\lambda_t$ and $\lambda_c$. The operating time and/or cycles accumulated during a mission, in accordance with a specified (input) operating sequence, is continuously compared with the component's time and/or cycle to failure to determine whether it fails during the mission. The mission fails upon the failure of a component, provided no alternate component or mode of operation is available to replace the function supported by the failed component. The configuration of the system, as well as the sequence of events during the mission, is specified by input so that both system and mission configurations may be easily changed.

In all cases, man's functions were treated as a component in series with the SC hardware function which man's functions affected. Phase-functional relationships have already been shown.

Limitations of the program include:

1. It was designed to handle a maximum of 300 components.

2. Each component may support a maximum of 10 functions.

3. Each primary component may have 12 alternate components.

4. Each component may have 110 dependent components.

5. There may be a maximum of 250 functions.

6. Each function may have 12 modes.

7. There is a maximum of 59 time intervals.

8. There may be a maximum of 400 functions in the time function schedule.

9. The maximum number of missions is 32,678.

The running time of the program depends upon the number of components, the number of alternates for these components, the time and/or cycles to failure, the number of functions, the number of intervals, the confidence level criteria, and number of missions to be run. It has been found in the case of 104 components, 24 time intervals, and 50 functions that two to three missions will be processed per second.

Within the context of the program, the following definitions apply:

1. Component - Any device whose reliability can be expressed as $R = (e^{-\lambda_t T})\ (e^{-\lambda_c C})$ where $\lambda_T$ is the failure rate (constant by definition within the limits of the intended mission) in terms of failures per hour; $\lambda_C$ is the failure rate in terms of failures per cycle; T is the operating time in hours; and C is the number of

[redacted]

cycles accumulated in T hours. A component may be either cyclic or continuous where:

a. Cyclic reliability is calculated by $R = e^{-\lambda_c C}$ where C = n cycles

b. Continuous reliability is calculated either by $R = e^{-\lambda_t T}$

2. Primary component - A component that performs in the preferred mode of operation in a function.

3. Alternate component - A component that replaces a failed component. The alternate is one of the following types:

   a. Standby - An alternate that is turned on only when another alternate component has failed.

   b. Full-time redundant - An alternate which operates whenever the component it backs up operates, and which can act as a replacement in case of failure.

4. Dependent component - A component whose mode of operation is affected by the failure of another component. Its types are:

   a. Must fail - A component that must fail when the component on which it is dependent fails.

   b. Must not fail - A component that must not fail when the component on which it is dependent fails.

5. Mission - A set of functions occurring in a specified time sequence. The mission may be broken into time intervals of non-uniform length in which various functions are required.

6. Function - The characteristic action of a component or group of components. In the course of the operation of a function, components acquire operating cycles and/or operating time according to the discrete operating intervals of a function. A function may be:

   a. Critical - If its failure results in mission failure.

   b. Non critical - If its failure will not cause a mission failure.

7. Combinatorial Function - A function whose completion requires the operation of at least (R) of (N) components.



[redacted]

[redacted]

The Monte Carlo computer program may be summarized as follows:

1. Component(s) acquire operating time and/or cycles in accordance with time during which function(s) supported by the component(s) are required during a mission.

2. When operating time and/or cycles exceeds its randomly-generated operating time-to-failure or cycles-to-failure, a component fails.

3. When a component fails, an alternate part (if available) supports its function(s).

4. If there is no alternate part, an alternate mode (if available) is employed.

5. If there is no alternate mode, the function is failed.

6. Following a critical function failure, the mission is failed.

7. Of those functions which fail at a given time due to a component failure, the one chosen as the "cause" of mission failure is the first function listed in the input data as being supported by the failed component. If two or more components fail simultaneously, the one listed earliest in input data determines the function that caused the failure (i.e., in this case, the first function listed of those components which failed simultaneously is the "cause").

### 3.3.2 Crew Safety Reliability

The computation of crew safety reliability for those phases from launch through normal lunar stay is:

1. Establish the flight profile for mission abort from each of the phases under consideration as shown in Table 10.

2. Determine the sequence of events necessary for a safe return to earth from each mission phase.

3. Determine the S/C hardware and man's functions necessary to perform the required sequence of events.

4. Tabulate operating time on the components supporting the necessary functions for each abort sequence.

5. Compute reliability for each component for the abort sequences for each phase under consideration.

[redacted]

## Table 10. Crew Safety Profile

| Two-Man, Direct Flight Mission | | Lunar Orbital Rendezvous Mission | |
|---|---|---|---|
| Phase | Time in Abort (Hr) | Phase | Time in Abort (Hr) |
| 1. Launch to jettison of LET | 0.184 | 1. Launch to jettison of LET | 0.184 |
| 2. LET jettison through second-stage boost | 0.224 | 2. LET jettison through second-stage boost | 0.224 |
| 3. Earth parking orbit | 0.224 | 3. Earth parking orbit | 0.224 |
| 4. Translunar injection | 1.904 | 4. Translunar injection | 1.904 |
| 5. First midcourse correction | 3.054 | 5. LEM transfer | 2.404 |
| 6. Translunar coast - Period No. 1 | 23.554 | 6. First midcourse correction | 3.654 |
| 7. IMU alignment | 25.054 | 7. Translunar coast - Period No. 1 | 23.654 |
| 8. Translunar coast - Period No. 2 | 30.554 | 8. Inertial measuring unit alignment | 25.154 |
| 9. Translunar coast - Period No. 3 | 103.010 | 9. Translunar coast - Period No. 2 | 30.654 |
| 10. Navigation sightings - No. 1 | 94.010 | 10. Translunar coast - Period No. 3 | 102.981 |
| 11. Translunar coast - Period No. 4 | 93.010 | 11. Navigation sightings - No. 1 | 93.981 |
| 12. Navigation sightings - No. 2 | 78.010 | 12. Translunar coast - Period No. 4 | 92.981 |
| 13. Translunar coast - Period No. 5 | 77.010 | 13. Navigation sightings - No. 2 | 77.981 |
| 14. IMU alignment and navigation sightings | 66.510 | 14. Translunar coast - Period No. 5 | 76.981 |
| 15. Lunar orbit inject | 64.943 | 15. Inertial measuring unit alignment and navigation sightings | 66.481 |
| 16. Lunar orbit | 64.943 | 16. Lunar orbit inject | 64.943 |
| 17. Descend to elliptical perilune | 65.926 | 17. Lunar orbit | 64.943 |
| 18. Descend to 1000-feet altitude | 65.976 | 18. LEM entry, checkout, and separation | 65.443 |
| 19. Hover and landing maneuver | 65.976 | 19. LEM injection into elliptical orbit | 66.293 |
| 20. Lunar operations | 65.976 | 20. LEM approach operations | 66.293 |
| | | 21. LEM retrograde | 66.293 |
| | | 22. LEM Hover and landing | 66.293 |
| | | 23. Lunar operations - Period No. 1 | 66.293 |
| | | 24. Lunar operation and lunar orbit correction | 66.293 |



[redacted]

[redacted]

6. Construct reliability logic diagrams for each abort sequence.

7. Using computed component reliabilities in the reliability logic diagrams, calculate the probability of successful abort.

8. From the failure density distribution, which is an output of the Monte Carlo mission success model and the probability of successful abort, compute failed aborts per phase and crew safety reliability as

$$Q_A \times q_m = q_A$$

$$R_{cs} = \frac{N - q_A}{N}$$

where

$Q_A$ = probability of failing the abort

$q_m$ = number of failed missions

$q_A$ = number of failed aborts

$N$ = number of attempted missions

$R_{cs}$ = crew safety reliability

9. As indicated previously, crew safety and mission success are synonomous for phases beyond normal lunar stay and are derived from the computer program.

## 3.4 DISCUSSION

Reliability by phase for each of the eight configurations studied is listed in Tables 11 and 12. These tables treat booster reliabilities, which were furnished by NASA, as being serially related to the spacecraft—inasmuch as they were developed to support a serial reliability configuration. Possible data relationships to a compound reliability configuration could not be discerned immediately from supplied data. The tabulations, therefore, show spacecraft reliabilities by phase; integrated spacecraft, booster, and integrated booster reliabilities separately.

For the "perfect" man ($R_{man}$ = 1), there is no significant difference in mission success probability between two mission modes for configurations

[redacted]

| Phase Description | Phase Time (hr) |
|---|---|
| 1. Launch to jettison of LET | 0.04 |
| 2. LET jettison through second stage boost | 0.09 |
| 3. Earth-parking orbit | 1.13 |
| 4. Translunar injection | 0.10 |
| 5. LEM transfer | 0.50 |
| 6. First midcourse correction | 2.50 |
| 7. Translunar coast - Period No. 1 | 20.00 |
| 8. IMV alignment | 1.50 |
| 9. Translunar coast - Period No. 2 | 5.50 |
| 10. Translunar coast - Period No. 3 | 9.00 |
| 11. Navigation sightings No. 1 | 1.00 |
| 12. Translunar coast - Period No. 4 | 15.00 |
| 13. Navigation sighting No. 2 | 1.00 |
| 14. Translunar coast - Period No. 5 | 10.50 |
| 15. IMV alignment and navigation sightings | 2.56 |
| 16. Lunar orbit inject | 0.03 |
| 17. Lunar orbit | 1.82 |
| 18. LEM entry, checkout and separation | 0.78 |
| 19. LEM injection into elliptical orbit | 0.00 |
| 20. LEM approach operations | 0.49 |
| 21. LEM retrograde | 0.10 |
| 22. LEM hover and landing | 0.02 |
| 23. Lunar operations - Period No. 1 | 21.50 |
| 24. Lunar operations and lunar orbit correction | 2.50 |
| 25. Emergency lunar operations | 21.50 |
| 26. Lunar emergency orbit correction | 2.50 |
| 27. LEM lunar launch | 0.10 |
| 28. LEM rendezvous | 0.85 |
| 29. LEM docking and separation | 0.50 |
| 30. Postlanding lunar orbit | 1.08 |
| 31. Transearth inject | 0.02 |
| 32. Transearth midcourse correction No. 1 | 3.00 |
| 33. Transearth coast - Period No. 1 | 23.00 |
| 34. Navigation alignment | 2.00 |
| 35. Transearth coast - Period No. 2 | 4.00 |
| 36. Navigation sightings - transearth | 1.50 |
| 37. Transearth coast - Period No. 3 | 26.85 |
| 38. Final midcourse correction | 2.00 |
| 39. S/M separation | 0.01 |
| 40. Earth entry | 0.37 |
| 41. Deploy drogue chute through landing | 0.18 |
| Spacecraft reliability | |
| Booster reliability | |
| 1st stage | |
| 2nd stage | |
| 3rd stage | |
| Total mission reliability | |

Table 11. Reliability and Phase Relationships for Apollo LOR, 186-Hour Mission

| Running Time (hr) | Mission Success Reliability | | | | Crew Safety Reliability | Probability of Safe Abort |
|---|---|---|---|---|---|---|
| | Man = 1 W/O Maint | Man = 1 W/Maint | Man<1 W/O Maint | Man<1 W/Maint | Man<1 W/Maint | Man<1 W/Maint |
| 0.042 | — | — | 0.9992 | 0.9994 | 0.99999 | 0.9861 |
| 0.140 | 0.9998 | — | 0.9988 | 0.9982 | 0.99996 | 0.9793 |
| 1.273 | 0.9816 | 0.9908 | 0.9814 | 0.9868 | 0.99973 | 0.9793 |
| 1.373 | 0.9976 | 0.9977 | 0.9971 | 0.9986 | 0.99995 | 0.9632 |
| 1.873 | 0.9937 | 0.9941 | 0.9912 | 0.9961 | 0.99986 | 0.9630 |
| 4.373 | 0.9611 | 0.9759 | 0.9638 | 0.9790 | 0.99918 | 0.9610 |
| 24.373 | 0.9897 | 0.9895 | 0.9826 | 0.9864 | 0.99912 | 0.9352 |
| 25.873 | 0.9751 | 0.9863 | 0.9797 | 0.9905 | 0.99936 | 0.9332 |
| 31.373 | 0.9986 | 0.9987 | 0.9980 | 0.9981 | 0.99986 | 0.9257 |
| 40.373 | 0.9971 | 0.9978 | 0.9967 | 0.9972 | 0.99954 | 0.8359 |
| 41.373 | 0.9806 | 0.9909 | 0.9846 | 0.9914 | 0.99868 | 0.8460 |
| 56.373 | 0.9959 | 0.9967 | 0.9950 | 0.9961 | 0.99941 | 0.8473 |
| 57.373 | 0.9867 | 0.9906 | 0.9854 | 0.9902 | 0.99869 | 0.8657 |
| 67.873 | 0.9988 | 0.9973 | 0.9977 | 0.9967 | 0.99956 | 0.8668 |
| 70.440 | 0.9643 | 0.9771 | 0.9635 | 0.9786 | 0.99744 | 0.8800 |
| 70.477 | 0.9997 | 0.9991 | 0.9993 | 0.9996 | 0.99995 | 0.8807 |
| 72.297 | 0.9995 | — | — | 0.9998 | 0.99997 | 0.8807 |
| 73.077 | 0.9980 | 0.9991 | 0.9911 | 0.9899 | 0.99879 | 0.8802 |
| 73.080 | — | — | 0.9920 | 0.9939 | 0.99925 | 0.8775 |
| 73.577 | 0.9983 | 0.9990 | 0.9956 | 0.9963 | 0.99955 | 0.8775 |
| 73.685 | 0.9992 | 0.9990 | 0.9906 | 0.9890 | 0.99865 | 0.8771 |
| 73.710 | — | — | 0.9781 | 0.9812 | 0.99769 | 0.8771 |
| 95.210 | 0.9927 | 0.9916 | 0.9519 | 0.9494 | 0.99378 | 0.8771 |
| 97.710 | 0.9601 | 0.9754 | 0.9628 | 0.9781 | 0.99730 | 0.8771 |
| 119.210 | 0.9936 | 0.9930 | 0.9769 | 0.9727 | 0.9727 | 0.9727 |
| 121.710 | 0.9982 | 0.9983 | 0.9878 | 0.9874 | 0.9874 | 0.9874 |
| 121.810 | 0.9997 | 0.9995 | 0.9994 | 0.9992 | 0.9992 | 0.9992 |
| 122.660 | 0.9971 | 0.9978 | 0.9928 | 0.9928 | 0.9928 | 0.9928 |
| 123.160 | 0.9997 | 0.9997 | 0.9605 | 0.9684 | 0.9684 | 0.9684 |
| 124.240 | — | — | 0.9982 | 0.9983 | 0.9983 | 0.9983 |
| 124.269 | — | — | — | 0.9997 | 0.9997 | 0.9997 |
| 127.269 | 0.9989 | 0.9995 | 0.9955 | 0.9970 | 0.9970 | 0.9970 |
| 150.269 | 0.9982 | 0.9981 | 0.9657 | 0.9711 | 0.9711 | 0.9711 |
| 152.269 | 0.9989 | 0.9995 | 0.9987 | 0.9983 | 0.9983 | 0.9983 |
| 156.269 | 0.9994 | 0.9997 | 0.9968 | 0.9977 | 0.9977 | 0.9977 |
| 157.769 | 0.9997 | 0.9997 | 0.9975 | 0.9989 | 0.9989 | 0.9989 |
| 184.619 | 0.9974 | 0.9978 | 0.9937 | 0.9744 | 0.9744 | 0.9744 |
| 186.619 | 0.9992 | 0.9997 | 0.9961 | 0.9985 | 0.9985 | 0.9985 |
| 186.629 | — | — | — | — | — | — |
| 186.999 | 0.9997 | — | 0.9810 | 0.9841 | 0.9841 | 0.9841 |
| 187.183 | 0.9994 | — | 0.9837 | 0.9826 | 0.9826 | 0.9826 |
| | 0.7758 | 0.843 | 0.5906 | 0.6550 | 0.8486 | 0.5612 |
| | 0.86374 | 0.86374 | 0.86374 | 0.86374 | 0.86374 | — |
| | 0.928405 | 0.928405 | 0.928405 | 0.928405 | 0.928405 | — |
| | 0.9932 | 0.9932 | 0.9932 | 0.9932 | 0.9932 | — |
| | 0.93672 | 0.93672 | 0.93672 | 0.93672 | 0.93672 | — |
| | 0.67009 | 0.728133 | 0.510125 | 0.56575 | 0.732970 | — |

[redacted]

| Phase Description |
| --- |
| 1. LET to jettison of LET |
| 2. LET jettison through second s |
| 3. Earth-parking orbit |
| 4. Translunar injection |
| 5. First midcourse correction |
| 6. Translunar coast - Period No. |
| 7. IMV alignment |
| 8. Translunar coast - Period No. |
| 9. Translunar coast - Period No. |
| 10. Navigation sightings - No. 1 |
| 11. Translunar coast - Period No. |
| 12. Navigation sightings - No. 2 |
| 13. Translunar coast - Period No. |
| 14. IMV alignment and navigation |
| 15. Lunar orbit inject |
| 16. Lunar orbit |
| 17. Descend to elliptical perilune |
| 18. Descend to 1000-foot altitude |
| 19. Hover and landing maneuver |
| 20. Lunar operations |
| 21. Emergency lunar operations |
| 22. Lunar launch - jettison LLM |
| 23. Lunar orbit maneuvers |
| 24. Transearth injection |
| 25. Transearth midcourse correc |
| 26. Transearth coast - Period No |
| 27. Navigation alignment |
| 28. Transearth coast - Period No |
| 29. Transearth navigation sightin |
| 30. Transearth coast - Period No |
| 31. Final midcourse correction |
| 32. S/M separation |
| 33. Earth entry |
| 34. Deploy drogue chute through l |
| Spacecraft reliability |
| Booster reliability |
| 1st stage |
| 2nd stage |
| 3rd stage |
| Total mission reliability |

T

| | Phase Time (hr) | Running Time (hr) | Mission Success Reliability | | | |
|---|---|---|---|---|---|---|
| | | | Man = 1 W/O Maint | Man = 1 W/Maint | Man<1 W/O Maint | Man< W/Ma |
| | 0.042 | 0.042 | — | — | 0.9994 | 0.999 |
| age boost | 0.098 | 0.140 | — | — | 0.9986 | 0.998 |
| | 1.133 | 1.273 | 0.9774 | 0.9864 | 0.9759 | 0.981 |
| | 0.1 | 1.373 | 0.9975 | 0.9966 | 0.9964 | 0.996 |
| | 2.50 | 3.873 | 0.9577 | 0.9750 | 0.9627 | 0.977 |
| 1 | 20.50 | 24.373 | 0.9895 | 0.9902 | 0.9843 | 0.983 |
| | 1.50 | 25.873 | 0.9738 | 0.9810 | 0.9762 | 0.985 |
| 2 | 5.50 | 31.373 | 0.9986 | 0.9991 | 0.9981 | 0.998 |
| 3 | 9.00 | 40.373 | 0.9988 | 0.9989 | 0.9972 | 0.998 |
| | 1.00 | 41.373 | 0.9812 | 0.9907 | 0.9867 | 0.993 |
| 4 | 15.00 | 56.373 | 0.9984 | 0.9970 | 0.9941 | 0.995 |
| | 1.00 | 57.373 | 0.9858 | 0.9898 | 0.9852 | 0.993 |
| 5 | 10.50 | 67.873 | 0.9986 | 0.9980 | 0.9964 | 0.996 |
| sightings | 2.567 | 70.440 | 0.9551 | 0.9753 | 0.9635 | 0.977 |
| | 0.037 | 70.477 | 0.9997 | 0.9998 | 0.9995 | 0.999 |
| | 1.890 | 72.367 | 0.9685 | 0.9812 | 0.9734 | 0.985 |
| | 0.983 | 73.350 | — | — | 0.9958 | 0.994 |
| | 0.050 | 73.400 | 0.9997 | — | 0.9998 | — |
| | 0.052 | 73.452 | — | 0.9998 | 0.9867 | 0.988 |
| | 24.000 | 97.452 | 0.9947 | 0.9961 | 0.9766 | 0.981 |
| | 24.000 | 121.452 | 0.9964 | 0.9961 | 0.9776 | 0.986 |
| | 0.079 | 121.531 | — | — | 0.9880 | — |
| | 1.580 | 123.111 | — | 0.9998 | 0.9984 | — |
| | 0.029 | 123.140 | — | — | — | 0.999 |
| ion No. 1 | 3.00 | 126.140 | 0.9997 | 0.9998 | 0.9979 | — |
| 1 | 23.00 | 149.140 | 0.9967 | 0.9958 | 0.9818 | 0.991 |
| | 2.00 | 151.140 | 0.9992 | 0.9995 | 0.9980 | 0.984 |
| 2 | 4.00 | 155.140 | 0.9994 | 0.9991 | 0.9969 | 0.998 |
| s | 1.50 | 156.640 | 0.9997 | — | 0.9987 | 0.991 |
| 3 | 26.850 | 183.490 | 0.9962 | 0.9963 | 0.9774 | 0.999 |
| | 2.000 | 185.490 | 0.9989 | 0.9993 | 0.9978 | 0.980 |
| | 0.010 | 185.500 | — | — | 0.9996 | 0.998 |
| | 0.370 | 185.870 | — | — | 0.9824 | 0.999 |
| anding | 0.184 | 186.054 | 0.9994 | — | 0.9814 | 0.98 |
| | | | 0.7862 | 0.8512 | 0.6826 | 0.78 |
| | | | 0.86374 | 0.86374 | 0.86374 | 0.86 |
| | | | 0.928405 | 0.9284 | 0.9284 | 0.92 |
| | | | 0.9932 | 0.9932 | 0.9932 | 0.99 |
| | | | 0.93672 | 0.93672 | 0.93672 | 0.93 |
| | | | 0.679073 | 0.735216 | 0.589589 | 0.67 |

ıble 12. Reliability and Phase Relationships for Apollo Two-Man, Direct Flight, 186-Hour Mission

| | Crew Safety Reliability | | Probability of Safe Abort | |
|---|---|---|---|---|
| :1 int | CS Man<1 W/Maint | CS Man<1 W/O Maint | Man<1 W/Maint | Man<1 W/O Maint |
| 0 | 0.99998 | 0.99999 | 0.9857 | 0.9848 |
| 2 | 0.99996 | 0.99997 | 0.9801 | 0.9792 |
| 7 | 0.99963 | 0.99930 | 0.9799 | 0.9709 |
| 9 | 0.99991 | 0.99985 | 0.9721 | 0.9579 |
| 3 | 0.99934 | 0.99833 | 0.9712 | 0.9551 |
| 2 | 0.99937 | 0.99894 | 0.9627 | 0.9325 |
| 1 | 0.99943 | 0.99824 | 0.9620 | 0.9318 |
| 1 | 0.99992 | 0.99985 | 0.9592 | 0.9186 |
| 3 | 0.99988 | 0.99962 | 0.9286 | 0.8659 |
| 5 | 0.99954 | 0.99824 | 0.9302 | 0.8674 |
| 2 | 0.99966 | 0.99921 | 0.9303 | 0.8675 |
| 8 | 0.99962 | 0.99862 | 0.9378 | 0.8837 |
| 7 | 0.99980 | 0.99958 | 0.9382 | 0.8841 |
| 8 | 0.99874 | 0.99612 | 0.9434 | 0.8926 |
| 3 | 0.99996 | 0.99995 | 0.9444 | 0.9027 |
| 9 | 0.99922 | 0.99742 | 0.9444 | 0.9027 |
| 9 | 0.99971 | 0.99955 | 0.9426 | 0.8929 |
| — | — | 0.99998 | 0.9426 | 0.8929 |
| 7 | 0.99935 | 0.99958 | 0.9426 | 0.8929 |
| 3 | 0.99892 | 0.99749 | 0.9426 | 0.8929 |
| 9 | 0.9869 | 0.9774 | 0.9869 | 0.9774 |
| — | — | 0.9879 | — | 0.9879 |
| — | — | 0.9983 | — | 0.9983 |
| 5 | 0.9995 | — | 0.9995 | — |
| — | — | 0.9979 | — | 0.9979 |
| 76 | 0.9976 | 0.9816 | 0.9976 | 0.9816 |
| 40 | 0.9840 | 0.9979 | 0.9840 | 0.9979 |
| 35 | 0.9985 | 0.9968 | 0.9985 | 0.9968 |
| 78 | 0.9978 | 0.9986 | 0.9978 | 0.9986 |
| 93 | 0.9993 | 0.9771 | 0.9993 | 0.9771 |
| 66 | 0.9866 | 0.9977 | 0.9866 | 0.9977 |
| 80 | 0.9980 | 0.9994 | 0.9980 | 0.9994 |
| 92 | 0.9992 | 0.9822 | 0.9992 | 0.9822 |
| 39 | 0.9839 | 0.9812 | 0.9839 | 0.9812 |
| 22 | 0.9367 | 0.8902 | 0.7094 | 0.6541 |
| 374 | 0.86374 | 0.86374 | — | — |
| 34 | 0.9284 | 0.9284 | — | — |
| 32 | 0.9932 | 0.9932 | — | — |
| 672 | 0.93672 | 0.93672 | — | — |
| 5618 | 0.809066 | 0.768902 | — | — |



[redacted]

with and without maintenance. The similarity is particularly striking when one considers the increased complexity of hardware in the LOR mission.

The major cause of failures in both missions is due to navigation and guidance electronics. The difference in the number of these N&G failures in the DF and LOR missions negates the expected lower LOR mission reliability due to increased systems complexity. Although the equipments are identical for both missions, the LOR mission contains two sets of N&G equipments (one in the C/M and one in the LEM). In the DF mission, N&G electronics in the command module is used to perform the critical functions necessary to land the spacecraft on the lunar surface. In the LOR mission a "second" set of N&G electronics in the lunar excursion module performs the same functions. Inasmuch as N&G electronics in the LEM has no prior operating time, the probability of successfully performing the N&G landing functions with these equipments in the LOR mission is better than in the DF mission (wherein these equipments have performed all N&G functions for prior phases).

The addition of inflight maintenance to the DF and LOR mission configurations again effected improvements in mission success reliability. This was to be expected, since equipments affected by inflight maintenance in both missions were the same.

The in-flight maintenance concept employed was that of modular replacement and it was applied to spacecraft electronic systems only. This modular concept involves the replacement of major functional modules and thus requires little or no "trouble shooting." Because they are designed for ease of removal and installation, the modules require minimal crew performance. Therefore, the probability of successfully performing required inflight maintenance functions was assumed to be equal to one. Only five replacement modules, each identical with the initially installed component, were considered. They were:

1. Power servo amplifiers (PSA)
2. Apollo guidance computer (AGC)
3. Intercommunications (Intercom)
4. Inertial reference package (IRP)
5. Electronics controls assembly (ECA)

Having established the level of the spacecraft hardware reliabilities for both missions considering "perfect" crews, the unreliability of man's performance was next determined. Figures 6 to 11 show discrete and

[redacted]

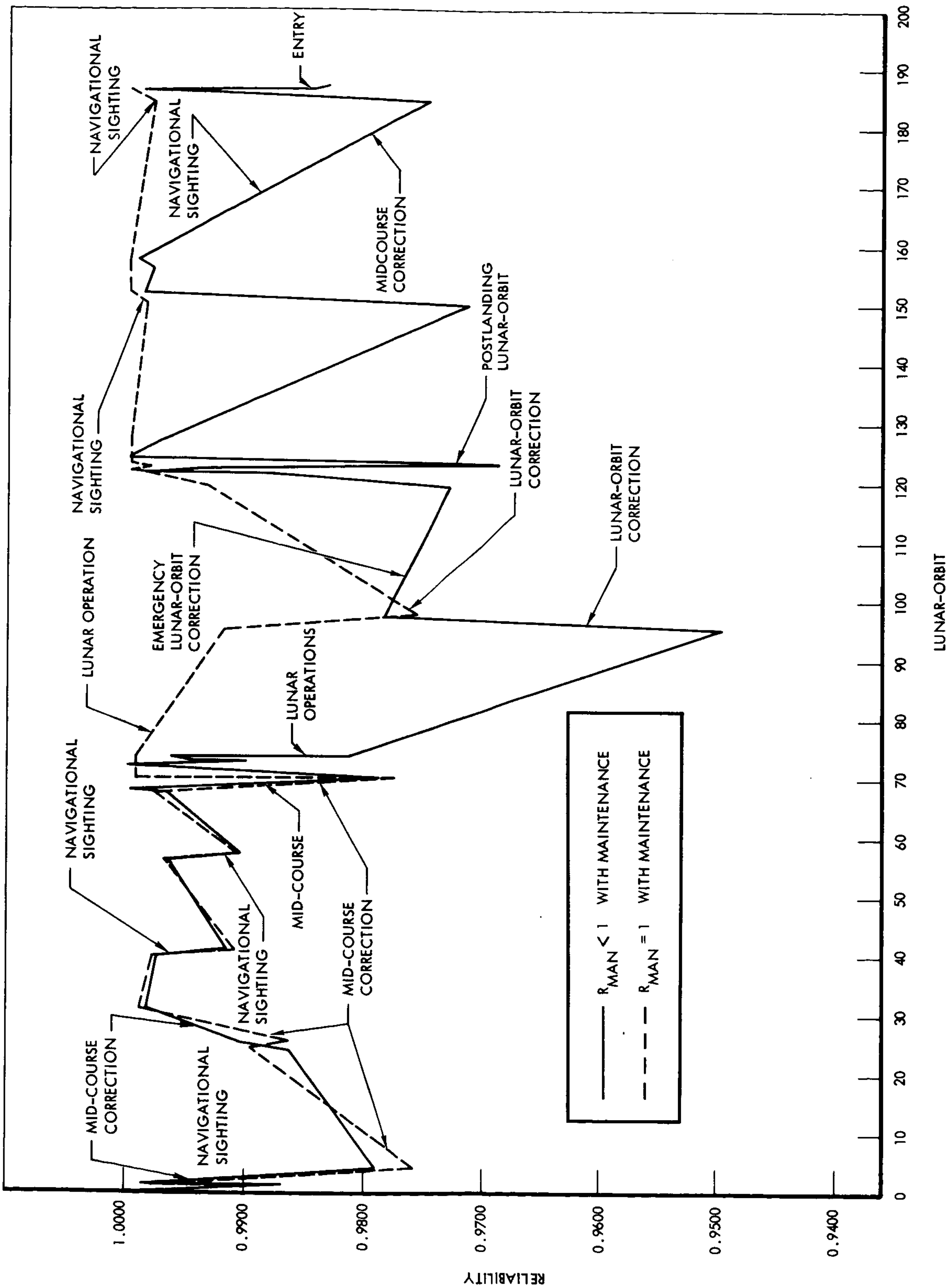


Figure 6. Lunar Orbital Rendezvous Discrete Mission Success Probability



[redacted]

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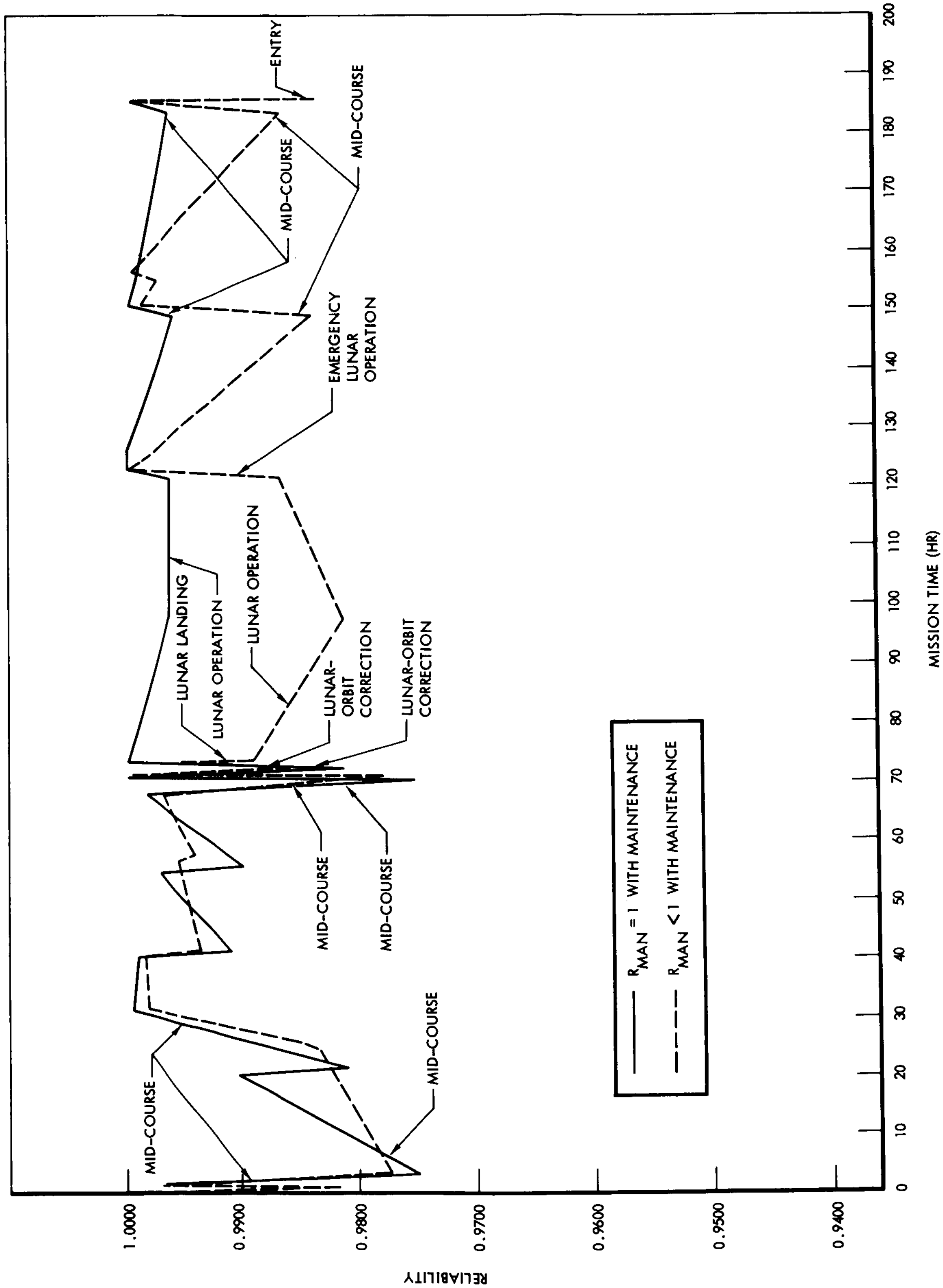


Figure 7. Two-Man, Direct Flight Discrete Mission Success Probability

[redacted]

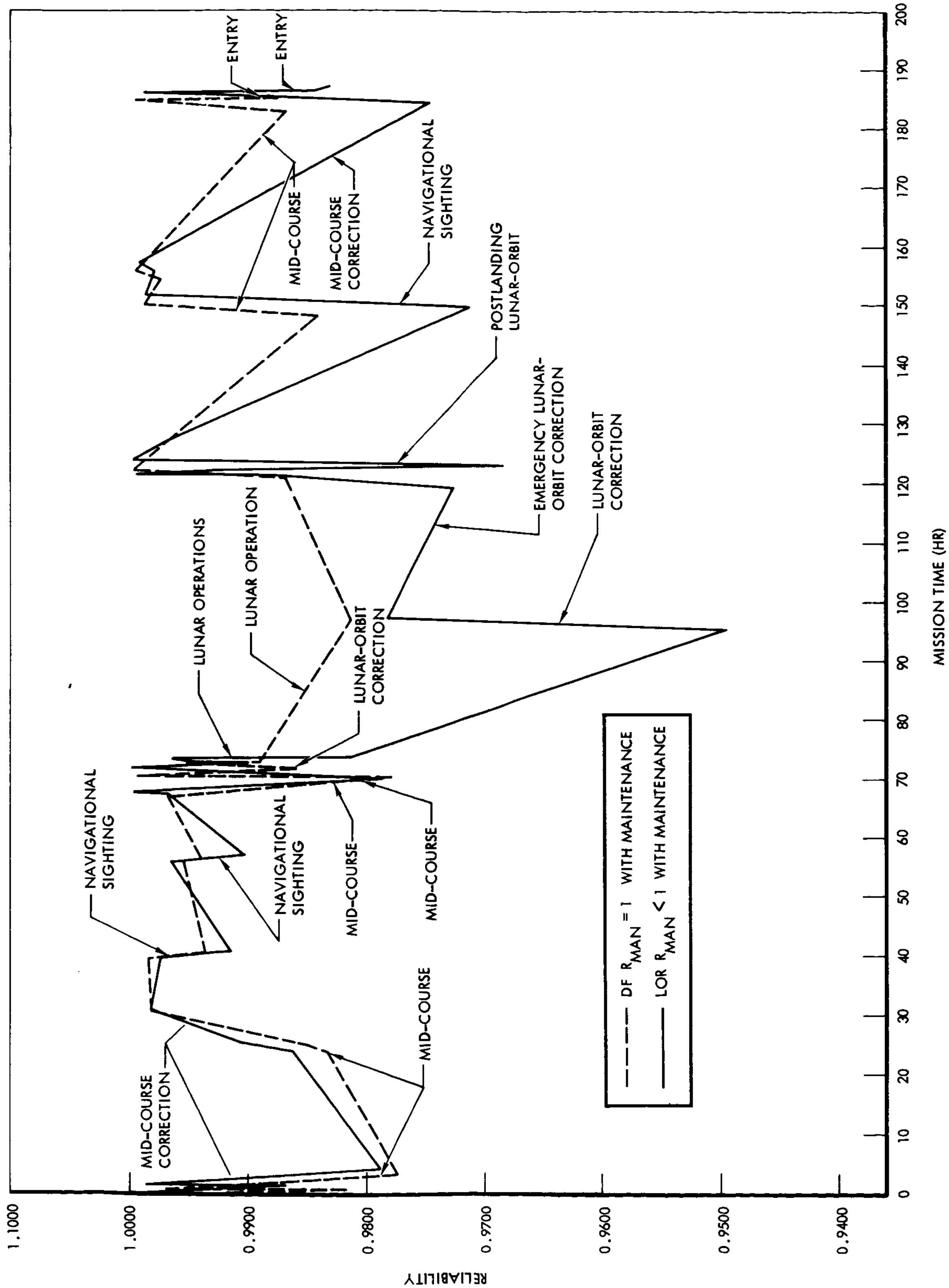


Figure 8. Lunar Orbital Rendezvous and Direct Flight Discrete Mission Success Comparison



[redacted]

[redacted]

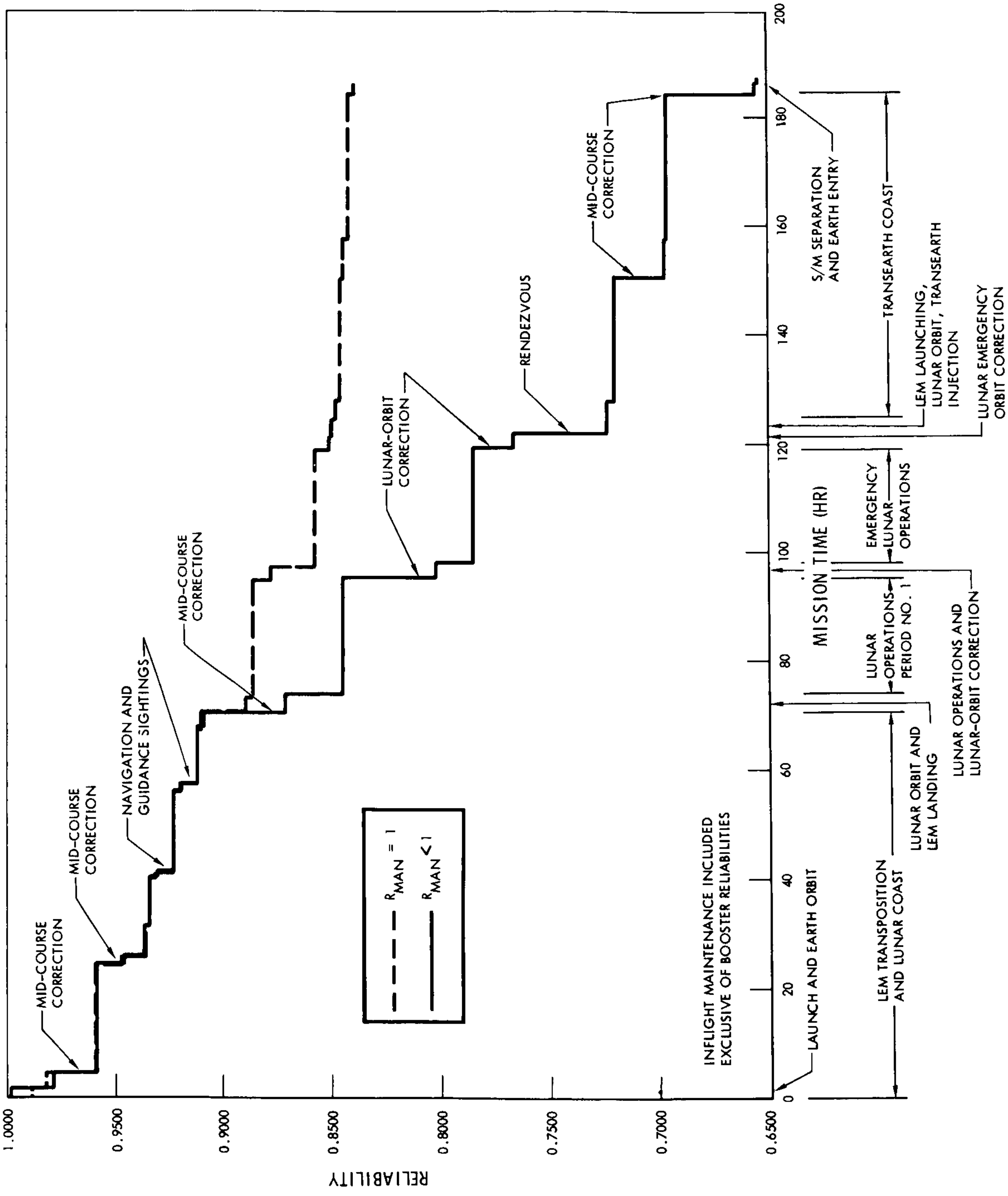


Figure 9. Cumulative Success Probability of the Apollo Lunar Orbital Rendezvous Mission

[redacted]

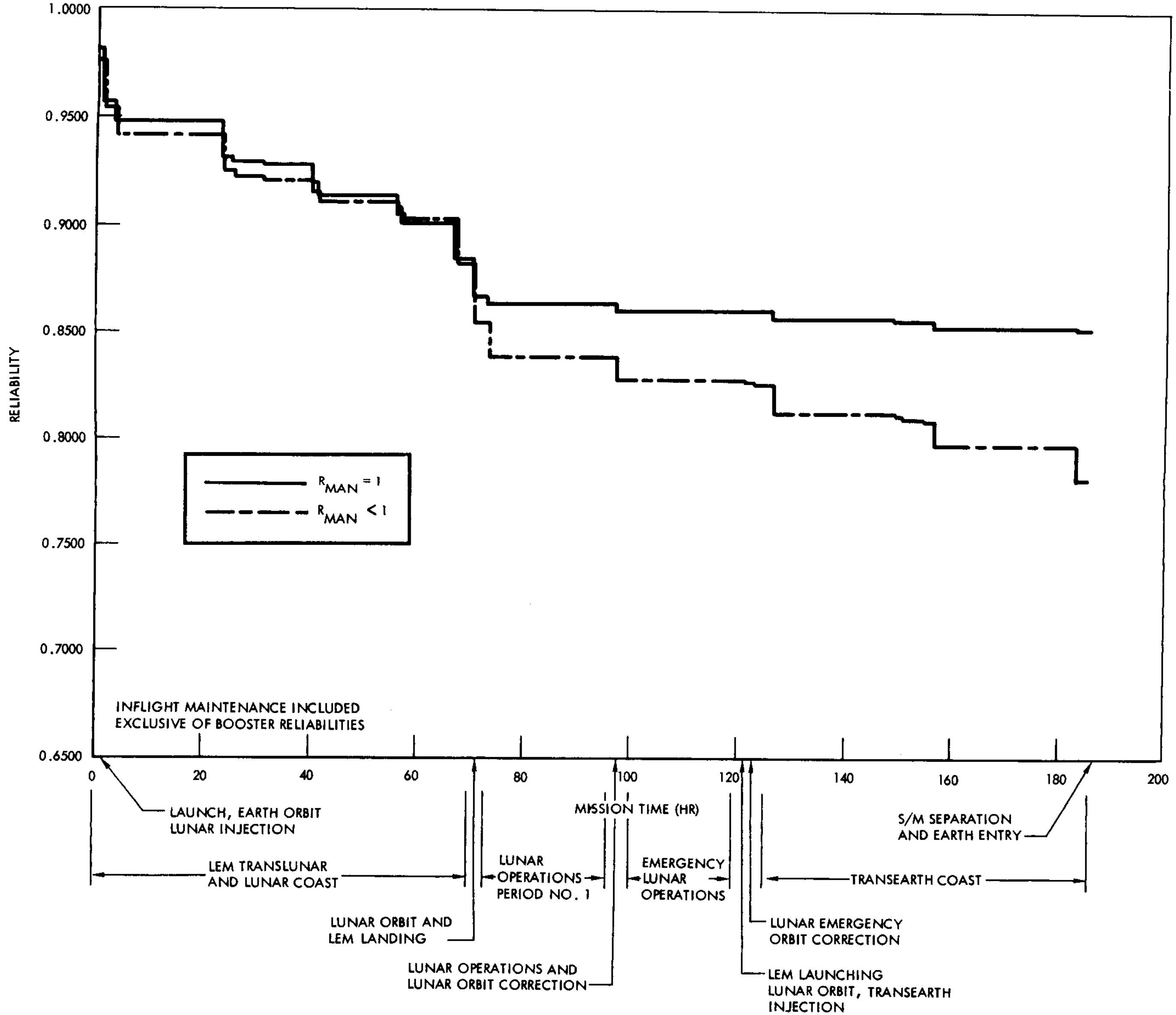


Figure 10. Cumulative Success Probability of the Two-Man, Direct Flight Mission

[redacted]

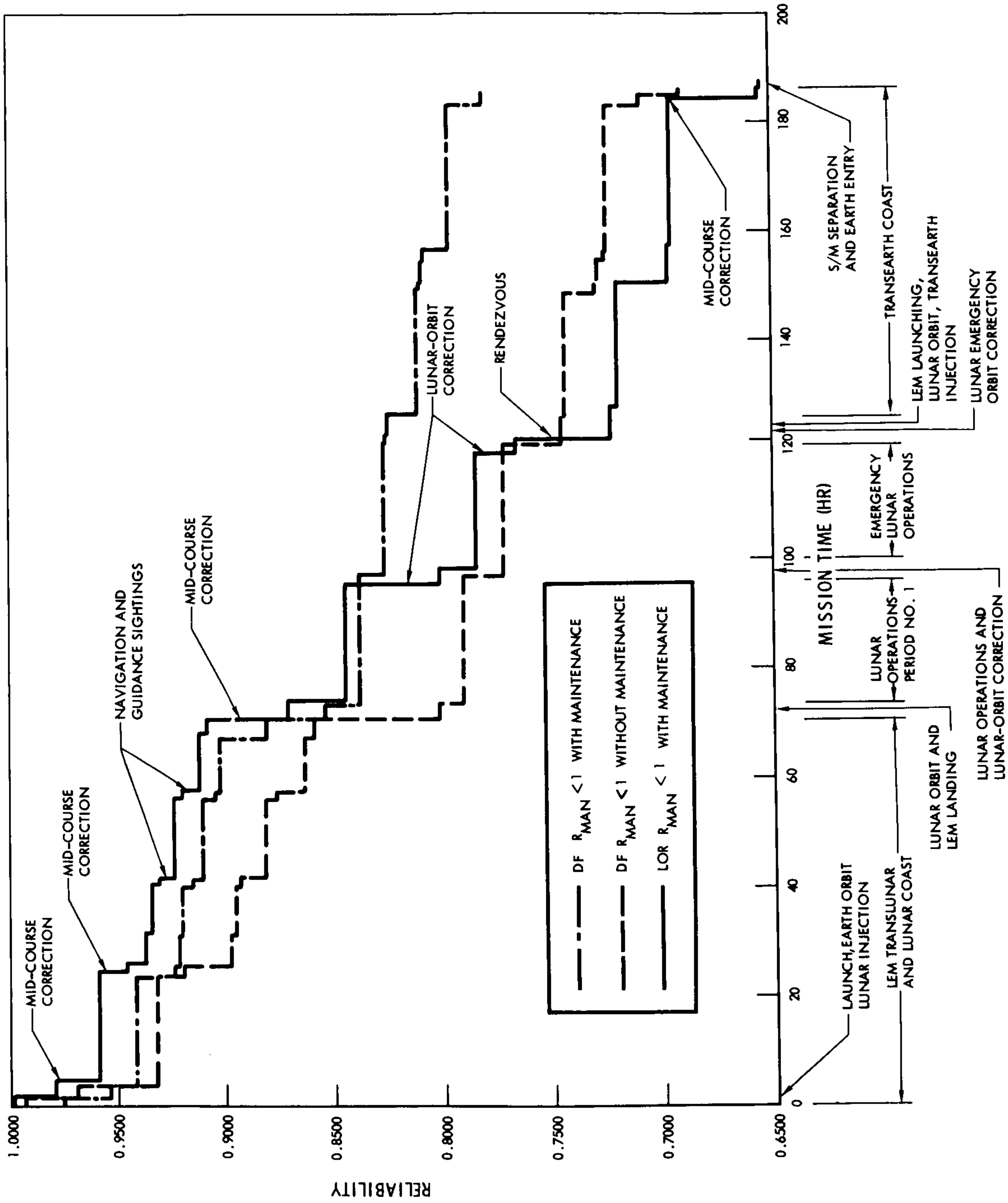


Figure 11. Summary Comparison of LOR and DF Cumulative Mission Success Probability



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cumulative effects of man's performance on mission success probability. The curves all start from an initial reliability of 1.0000 and are designed to show the variation of mission reliability as a function of time. Booster reliabilities are not included; but, inasmuch as they were assumed to be the same for each mode, relative rankings of the postlaunch phases are valid. (Absolute values can be derived by multiplying by booster reliabilities in Tables 11 and 12.)

For the LOR mission, man's performance begins to significantly degrade reliability after the commencement of cis-lunar operations — when the complexity of man's functions and environmental stresses are greatest. While some increase in the rate of reliability degradation occurs in the DF mission from the point of cis-lunar operations, degradation is not as severe as in the LOR mission.

Major cis-lunar failures in the LOR mission occur during lunar orbital corrections performed by the spacecraft. One man in the spacecraft must perform all functions necessary to correct the flight path in exacting sequence during this period. A primary factor which accounts for differences in probability of mission success between the DF and LOR missions is the rendezvous requirement. As can be seen in Figures 6 and 9, a major degradation in reliability occurs at this point in the LOR mission. Lunar orbital rendezvous requires that the excursion module be launched and guided to the orbiting spacecraft at the same time the spacecraft is making orbital corrections needed to effect the rendezvous.

Although all major elements of both vehicles must function properly during rendezvous, the principal cause of failure in this phase is man's performance. This may be explained by the complexity of man's functions and the need to perform these functions under fatigue and high stress. The stresses of lunar operations in the LOR mission tire the crew sufficiently to affect their performance for the remainder of the flight. The stress on man in the DF mission during lunar operations is not as severe as those in the LOR mission, therefore crew fatigue is less in the DF mission. Consequently, the probability of man successfully performing the same functions in the DF mission as in the LOR mission during transearth flight is greater.

Figures 8 and 11 show that man's performance in the DF does not degrade mission success to the same degree as it does in the LOR mission. There is some question as to the availability of sufficient volume in the two-man, DF command module to accommodate the maintenance replacement modules as presently conceived. However, even without maintenance, the two-man DF mission has a greater mission success probability than the LOR mission. Assuming the "perfect" man, it can be shown that most of the degradation in mission success reliability resulting from equipment failures can be negated by maintenance after the lunar operations phase. The rate of degradation of mission success reliability due to man's performance throughout the remainder of the flight is significantly less than in the DF than in the LOR mission.

Results of the crew safety studies parallel those of the mission success studies, as seen in Tables 11 and 12. However, the data need clarification to show the effect of man's performance on the crew safety reliability.

The crew safety reliability (Rcs) is defined as the probability of mission success (Rms) plus the product of the probability of mission failure (Qms) and the probability of safe abort (Ra), or:

$$(Rcs) = (Rms) + (Qms)\ (Ra)$$

A cursory inspection of the mission hardware indicates that the probability of safe abort in the LOR mode is greater than in the DF mission because LEM electronic components are interchangeable with those in the command module. Therefore the probability of successful abort in the event of electronic component failures also would be improved because failed components in the C/M could be replaced by components from the LEM for those phases of the mission prior to transearth injection. Inasmuch as the electronic components are the major cause of mission failure, abort success probability is improved by this interchangeability. Furthermore, successful abort in the LOR mission also is enhanced by the availability of LEM environmental control and electrical power systems as backups to their respective systems in the command module for aborts occurring in phases five through nine.

Although abort reliability for LOR mission appears better than for the DF mission when $R_{man} = 1$, the unreliability of man's performance in the LOR mission abort sequences is sufficiently great to reduce the probability of safe abort well below that of the DF mission. It is this effect of man's performance, plus the higher probability of mission failure in the LOR mission, that reduces the crew safety reliability of the LOR mission below that of the DF mission.

The mission success (MS) and crew safety (CS) reliabilities, employing the work-statement, launch-vehicle data are summarized in Table 13.

[redacted]

Table 13. Mission Reliability Summary

| Conditions of Configurations | Two-Man DF Mission | | Apollo LOR Mission | |
|---|---|---|---|---|
| | MS | CS | MS | CS |
| a. $R_{man}$ = 1, w/o maint | 0.6791 | -- | 0.6701 | -- |
| b. $R_{man}$ = 1, w/maint | 0.7352 | -- | 0.7281 | -- |
| c. $R_{man}$ < 1, w/o maint | 0.5896 | 0.7689 | 0.5101 | -- |
| d. $R_{man}$ < 1, w/maint | 0.6756 | 0.8091 | 0.5658 | 0.7330 |

Although complete information on the booster engine reliabilities was not available, recent tests indicate that booster reliabilities will be greater than those employed in this study. Listed below are booster engine reliabilities furnished in the work statement and predicted reliabilities for 1965:

| Boost Stage | NASA Reliabilities | 1965 Predicted Reliabilities |
|---|---|---|
| First | 0.9284 | 0.9605 |
| Second | 0.9932 | 0.9990 |
| Third (2 burns) | 0.9367 | 0.9899 |

This improvement in the launch reliability will increase mission success probability. The effect can be seen in Table 14.

Table 14. Mission Success Reliability Comparison
NASA vs Predicted Booster Reliabilities

| Conditions of Configuration | Two-Man DF Using Booster Reliabilities | | Apollo LOR Using Booster Reliabilities | |
|---|---|---|---|---|
| | Work Statement | 1965 Predicted | Work Statement | 1965 Predicted |
| $R_{man}$ = 1, w/o maint | 0.6791 | 0.7467 | 0.6701 | 0.7369 |
| $R_{man}$ = 1, w/maint | 0.7352 | 0.8085 | 0.7281 | 0.8007 |
| $R_{man}$ < 1, w/o maint | 0.5896 | 0.6483 | 0.5101 | 0.5610 |
| $R_{man}$ < 1, w/maint | 0.6756 | 0.7429 | 0.5658 | 0.6221 |



[redacted]

[redacted]

Although there is significant improvement in the probability of mission success with the predicted reliabilities of booster engines, the use of these predicted reliabilities would not affect the relative results of this study because the same booster engines were used in all configurations considered.

In summary, generated data clearly indicate that, with present Apollo in-flight maintenance concepts, the two-man, DF mission has a higher probability of success than the three-man, LOR mission. Granted, the reliability values for man's performance, the DF mission – even without maintenance – has a slight (but statistically significant) advantage over LOR mission reliability. The studies indicate that the mission success and crew safety reliabilities for the DF mode could be enhanced still further by having a third crewman to act as a back-up, should either of the other members be incapacitated.

The Monte Carlo computer program clearly identifies potential weaknesses in the complex sequence of events required for a successful mission. These then are amenable to be corrected. Further studies of this nature are needed to improve significantly mission success and crew safety reliabilities by bringing to light these weaknesses so that they may be corrected.

The requirement for a cryogenic service module propulsion system, as indicated by both the work statement and S&ID system studies, instigated an investigation of the reliability of a hydrogen-oxygen engine which would meet DF S/M performance requirements. Two hydrogen-oxygen engines are now under development. While single application of these engines would not meet reliability requirements, a reduced thrust engine could be developed to at least 0.96 reliability by 1965. Clustering four such engines in groups of two and using each group sequentially would result in a propulsion engine reliability of 0.99992. This exceeds the apportioned reliability requirement of 0.9999 as indicated by previous studies, for the service module propulsion engine in a DF mission.

## 4.0 SYSTEMS CONSIDERATIONS

A number of systems considerations implicit in the comparison of a two-man, direct flight, Apollo spacecraft and a three-man, LOR mission briefly were investigated. These included an examination of the constraints imposed, as well as benefits which might accrue due to a change in the size, volume, and weight of the presently conceived LOR configuration.

The two-man DF command module was assumed to be a scaled-down Apollo configuration with a base diameter of 120 to 123 inches and usable volume in the order of 40 $ft^3$/man. A preliminary design for such a S/C is shown in Drawing No. 3586-19. The crew was assumed to be in the 90th percentile. As can be seen, the seats cannot be fully extended. Available interior volumes were:

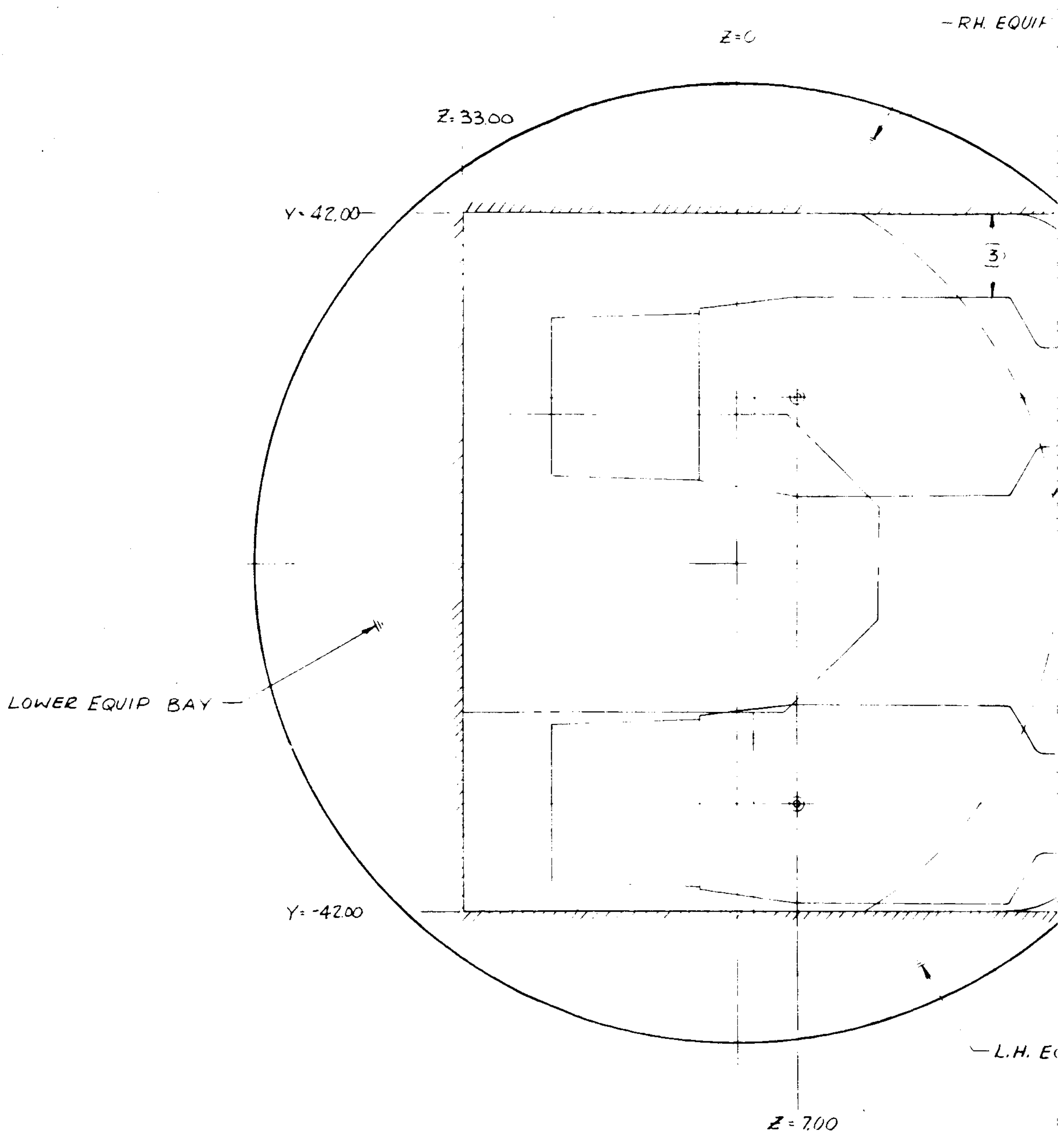
| | | |
|---|---|---|
| Inside mold line volume | = | 182 $ft^3$ |
| Equipment and displays | = | 100 $ft^3$ |
| Habitable volume | = | 82 $ft^3$ |

By comparison, the three-man, 154-inch-diameter Apollo C/M, shown in Drawing No. 3886-22, can sleep the crew in a fully-reclined position. Its interior volumes are:

| | | |
|---|---|---|
| Inside mold line volume | = | 366 $ft^3$ |
| Equipment and displays | = | 127 $ft^3$ |
| Habitable volume | = | 238.5 $ft^3$ |

Further preliminary weight estimates were made of the C/M and S/M equipments for an 186-hour (8-day) mission for both two- and three-man crews and 120- and 154-inch-diameter spacecraft. Current equipment weights for a 14-day (336-hour) mission, as reported in the September Apollo weight statement, were employed as a basepoint and modified to account for shorter mission time. Abbreviated time and reduction in the crew number results in less weight for crew, reaction control, environmental control, and earth landing systems, as well as useful load and electrical power requirements. The data are shown in Table 15. Also shown are data for two- and three-man capsules employing advanced state-of-the-art electronics (e.g., solid state, etc.) which will be available in the latter part of this decade.

[redacted]



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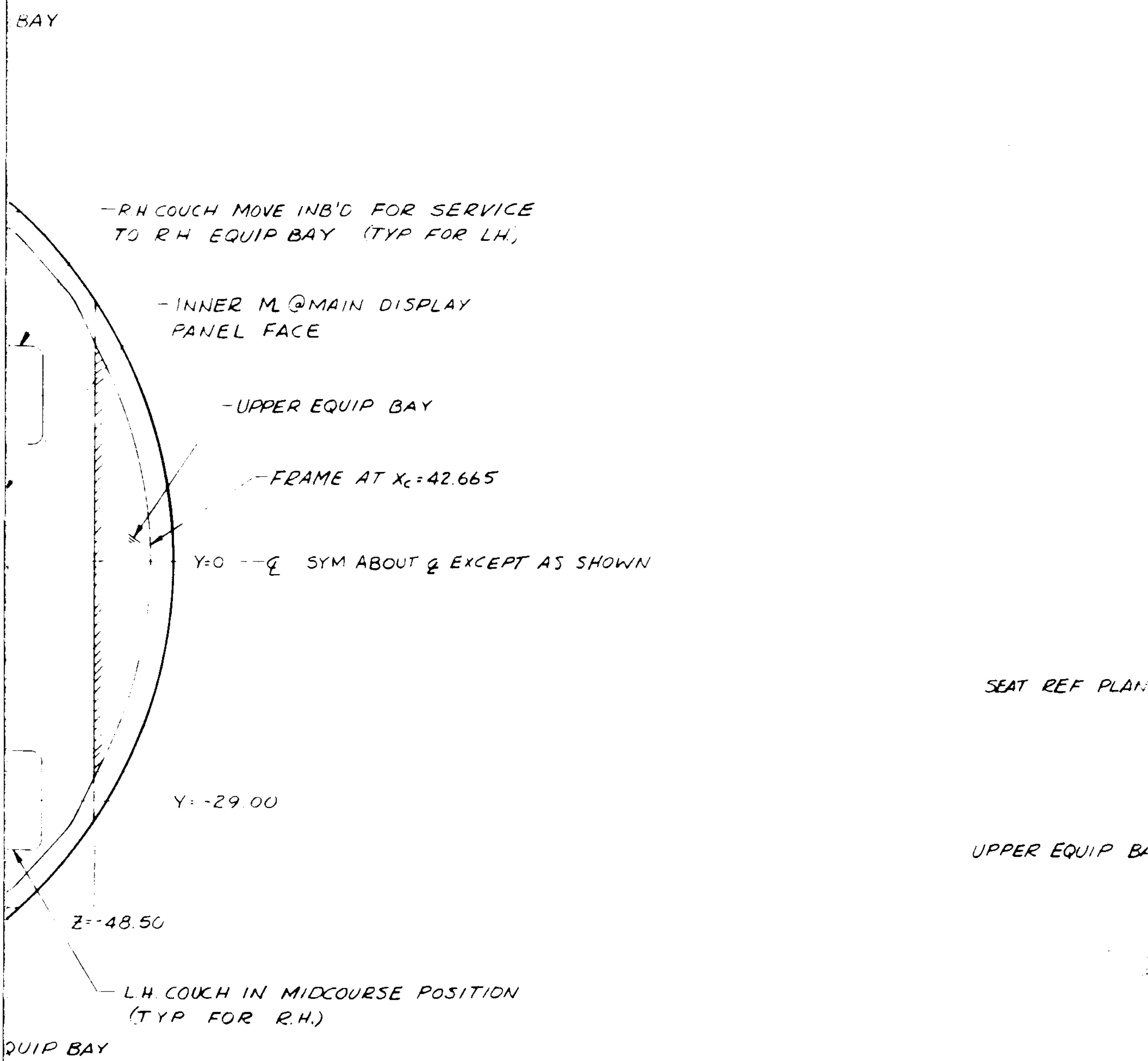
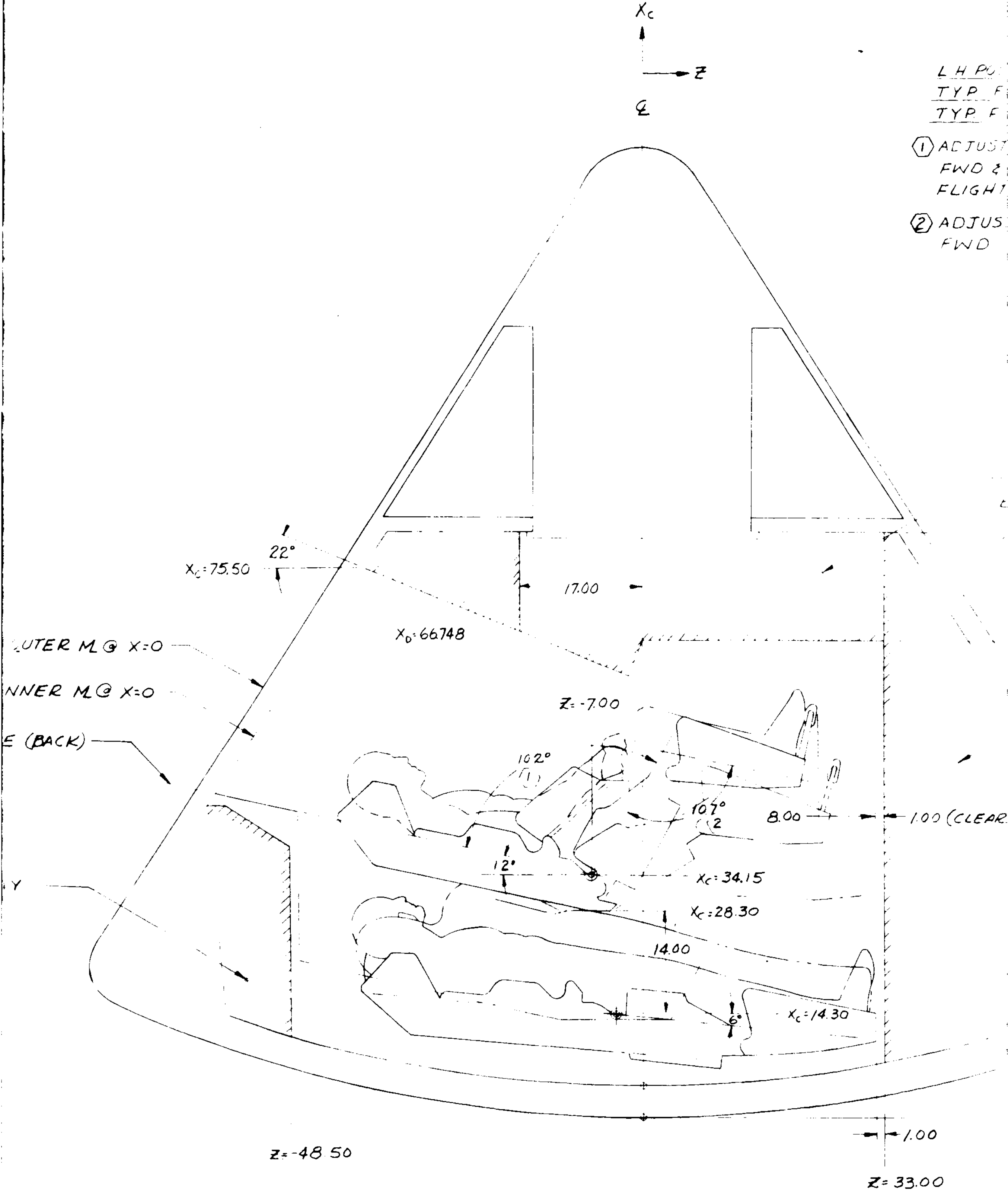
(FOR DESIGN OF PULL OUT DRAWERS,



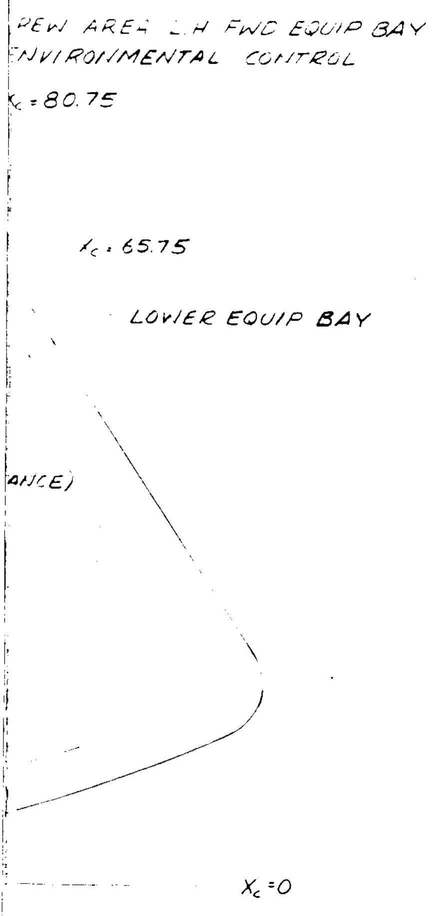


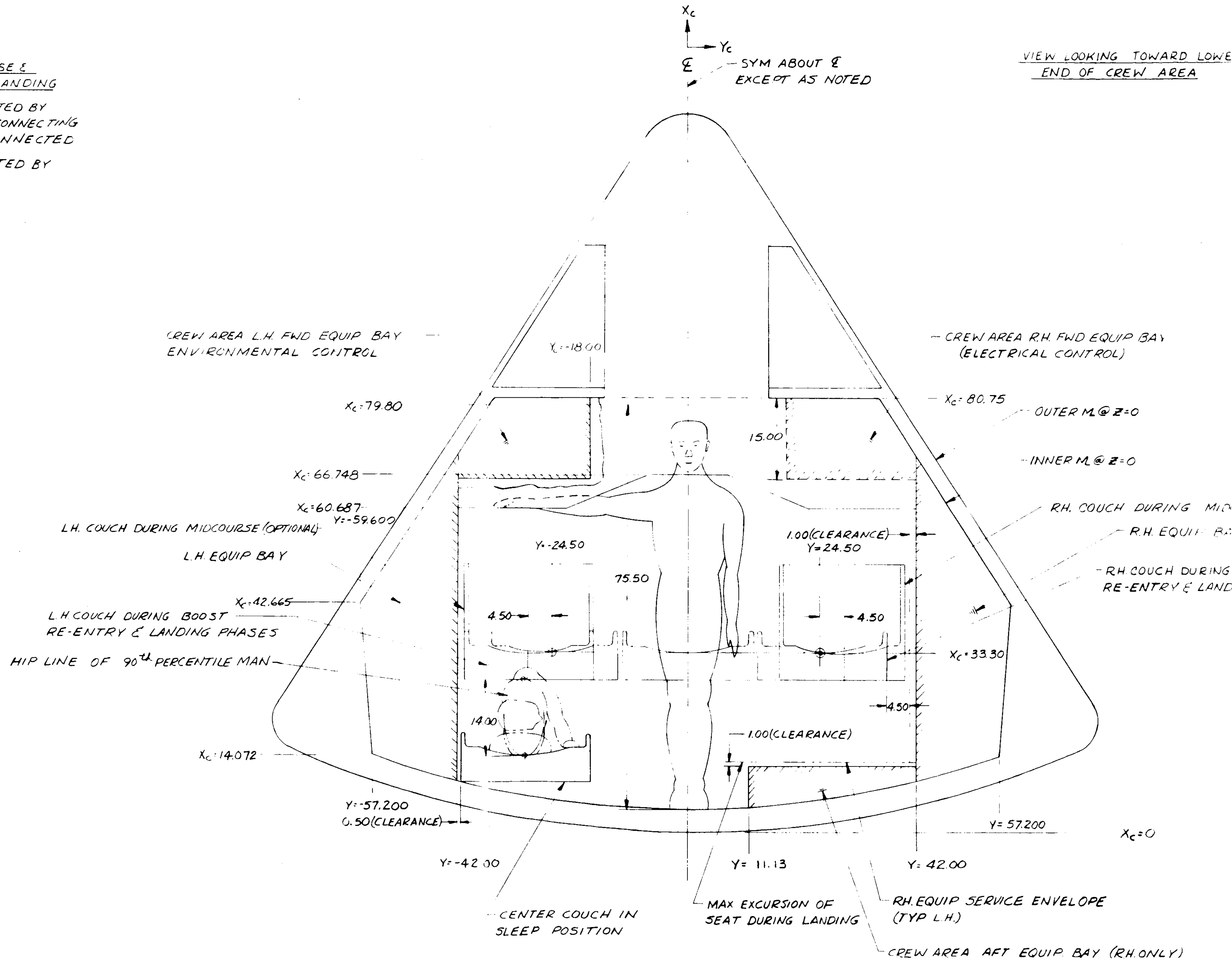
Xc
Z
℄
L H PO
TYP F
TYP F
(1) ACJUST
FWD &
FLIGH
(2) ADJUS
FWD
22°
Xc=75.50
17.00
X0=66.748
UTER ML @ X=0
NNER ML @ X=0
E (BACK)
Z=-7.00
102°
(1)
107°
(2)
8.00
1.00 (CLEAR.
12°
Xc=34.15
Xc=28.30
14.00
Y
6°
Xc=14.30
1.00
Z=-48.50
Z=33.00

TION FOR MIDCOURSE & LANDING
OR R.H POSITION DURING MIDCOURSE &
R ALL CREW MEMBERS FOR LAND LANDING

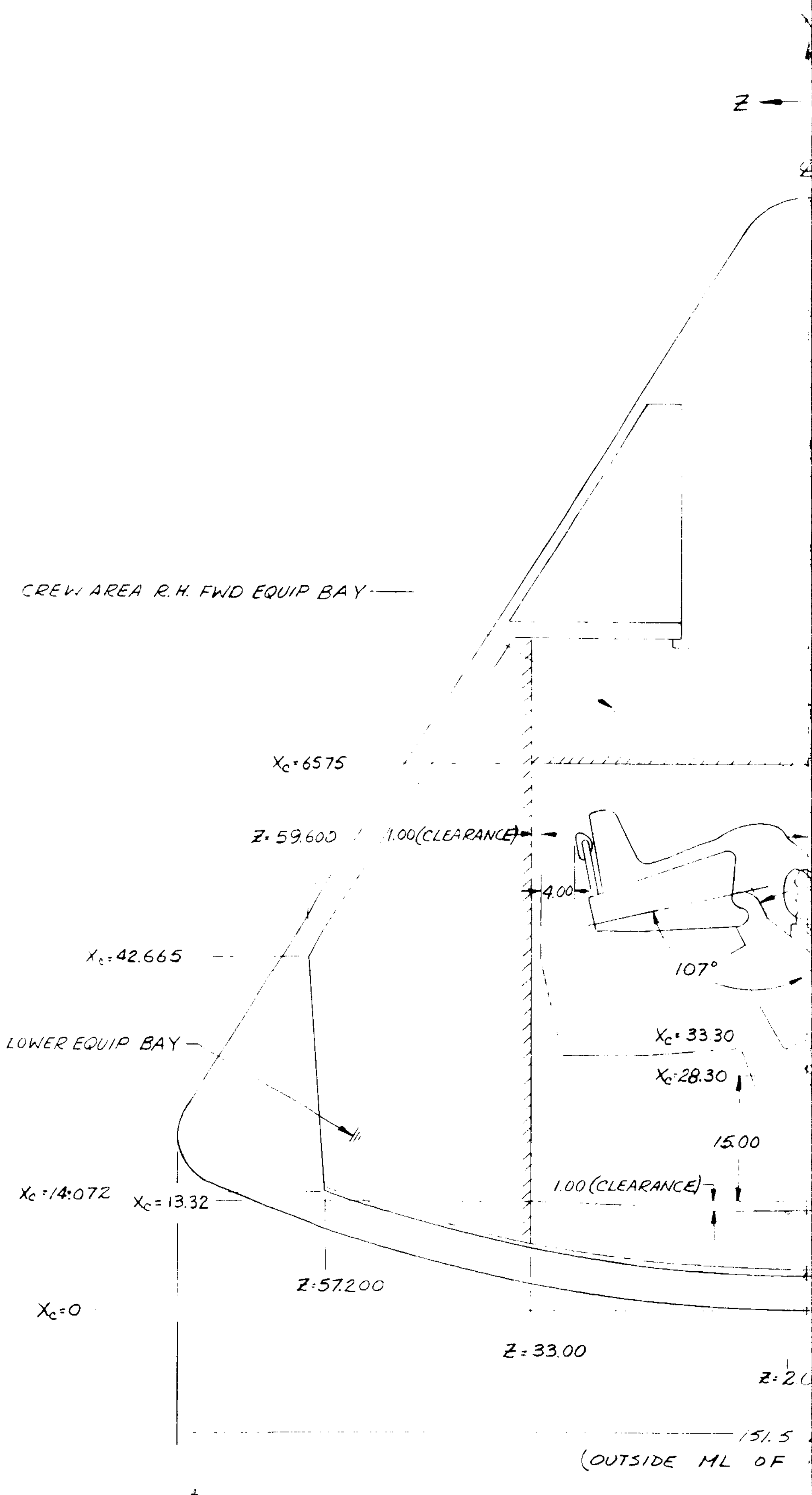
ABLE BETWEEN 90° & 135° AS LIMITED BY
LOWER EQUIP BAY WITHOUT DISCONNECTING
CONTROLS, 135° TO 180° IF DISCONNECTED

TABLE BETWEEN 30° & 180° LIMITED BY
EQUIP. BAY



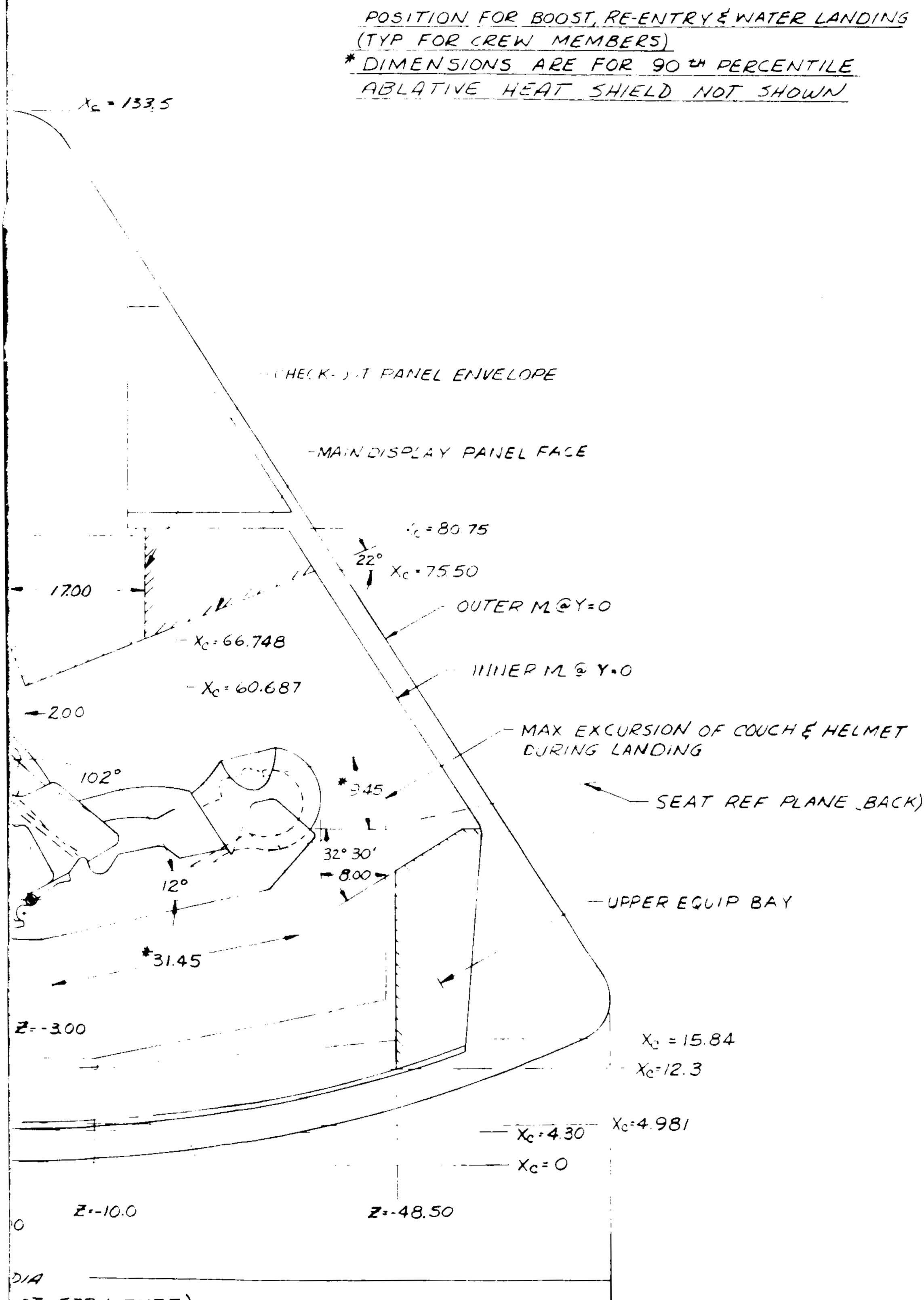



OURSE (OPTIONAL)
Y
BOOST
NG PHASES




Drawing

2




3586-22. Three-Man, 154-Inch-Diameter Apollo Command Module

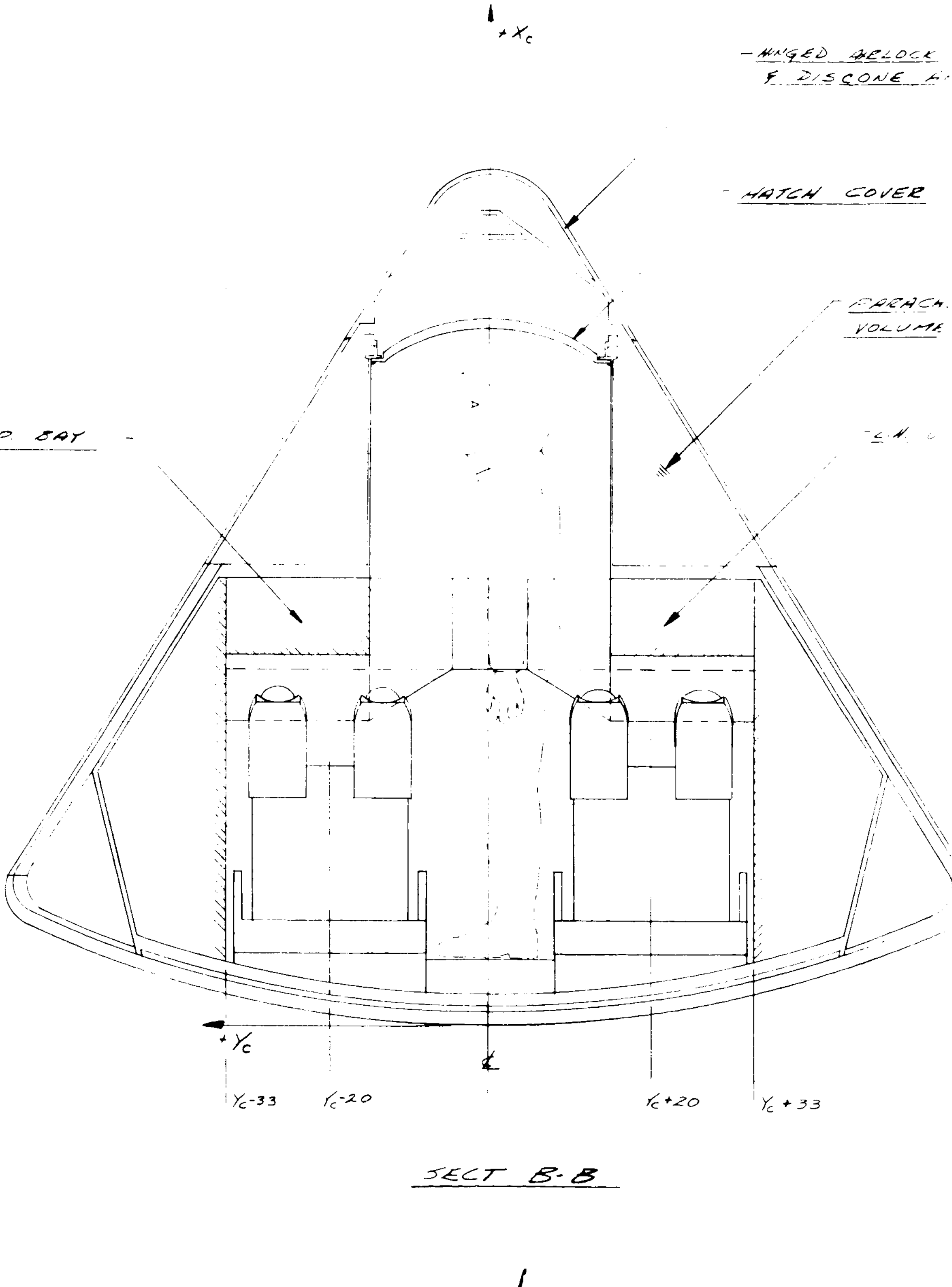


[redacted]

[redacted]

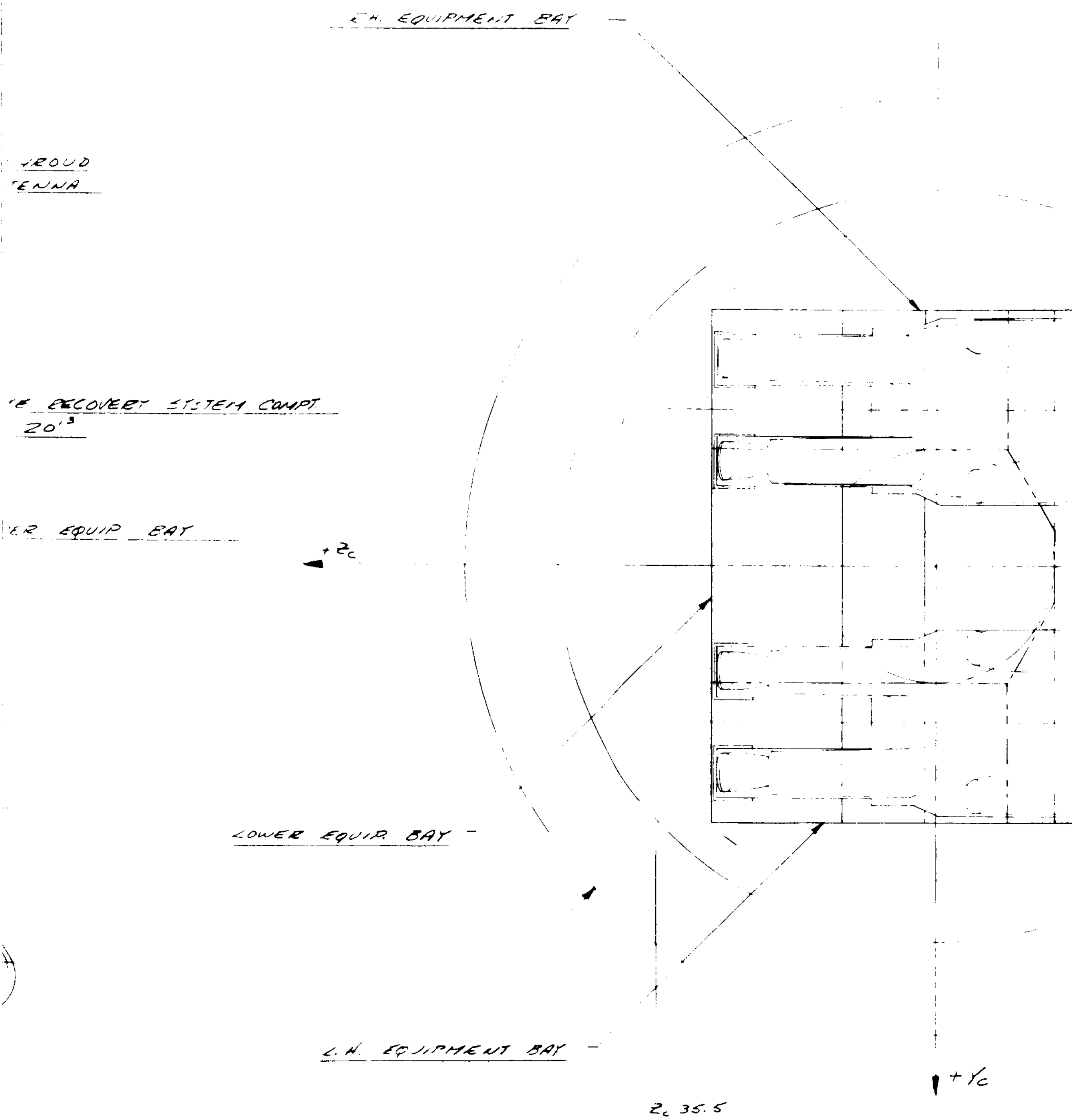
R.H.

IAL

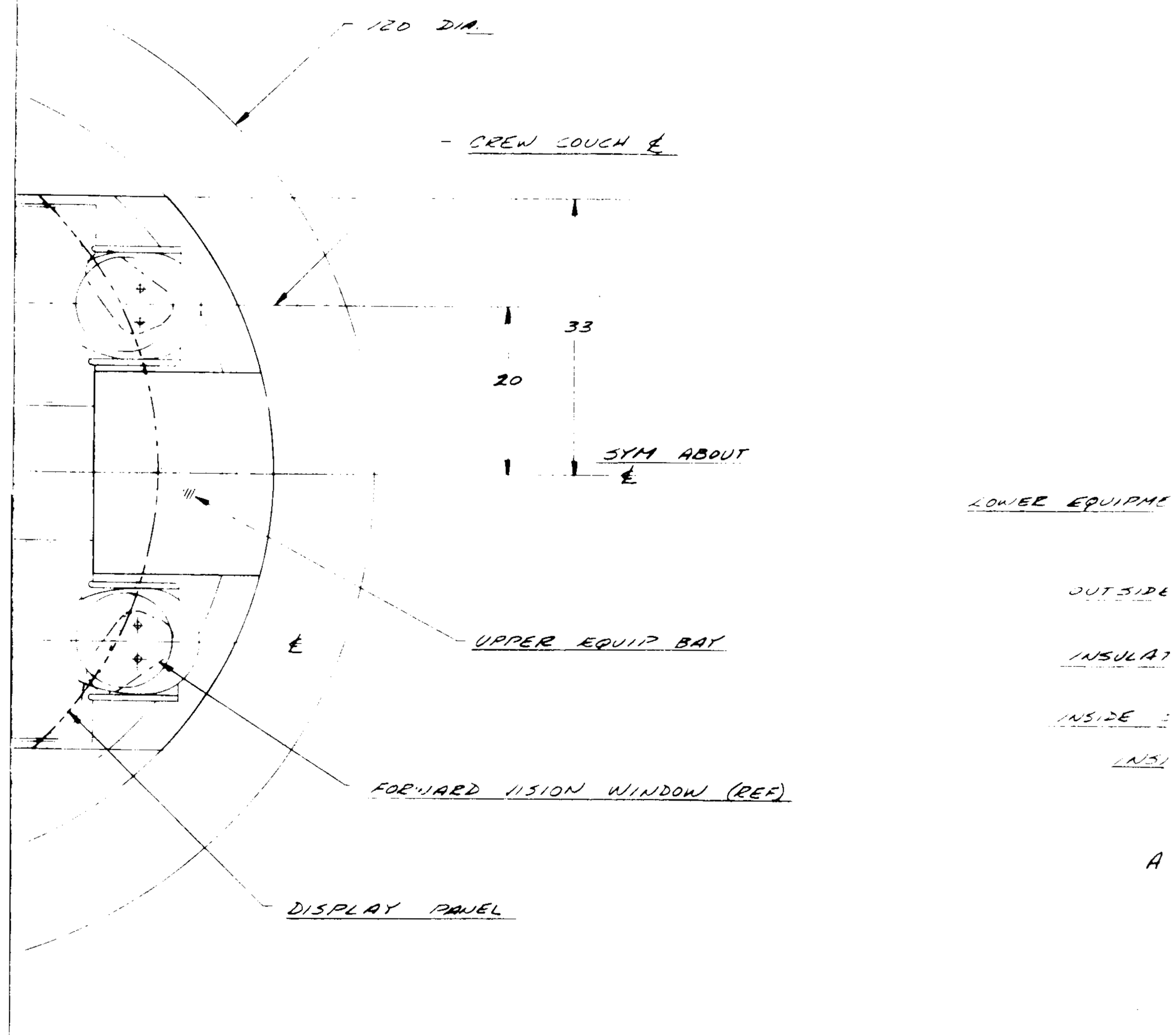

+Xc
HINGED AIRLOCK
& DISCONE A
HATCH COVER
PARACH.
VOLUME
UPPER EQUIP. BAY
+Yc
Yc-33
Yc-20
Yc+20
Yc+33

SECT B-B

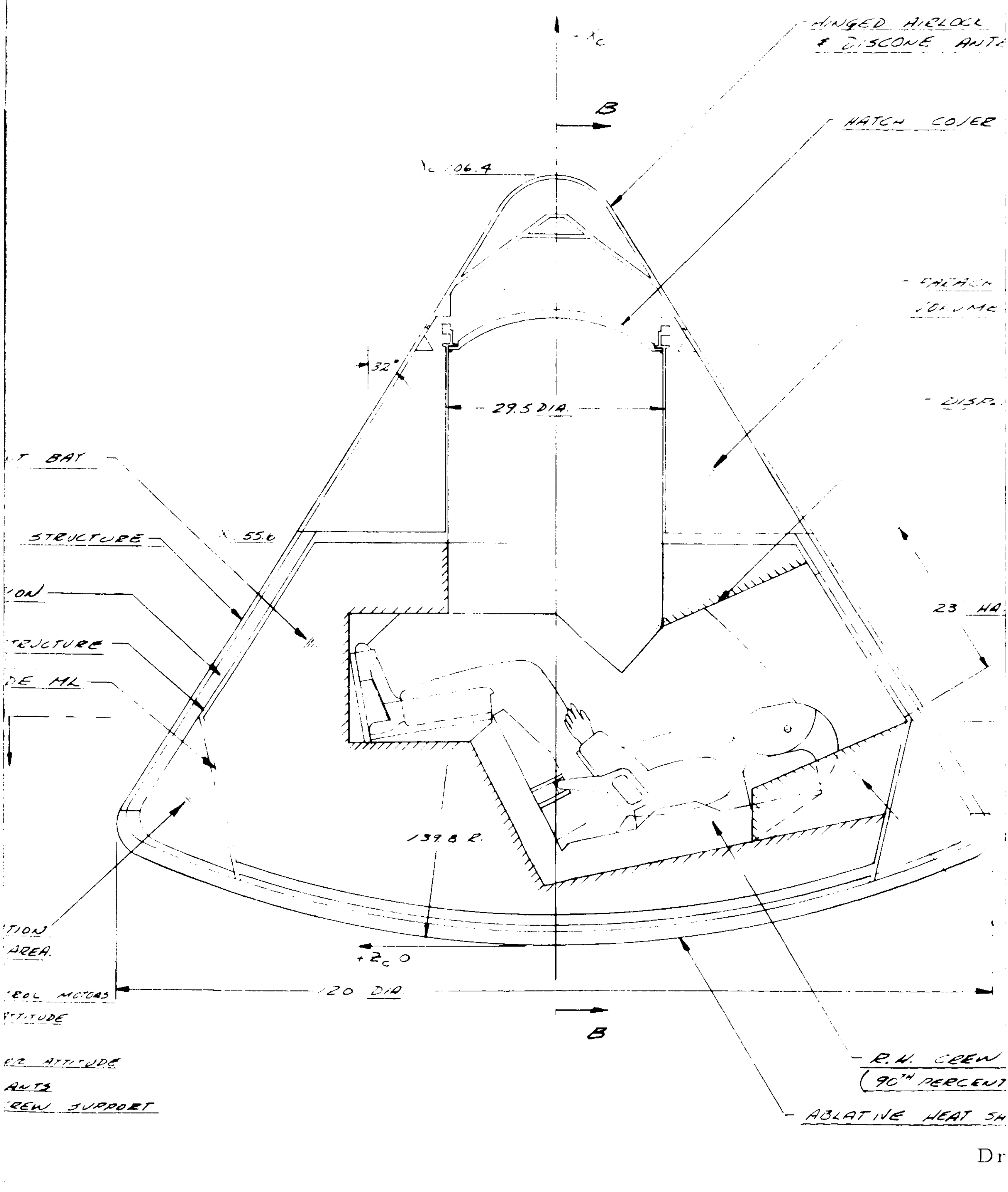
1


H. EQUIPMENT BAY
ROUD
ENNA
E RECOVERY SYSTEM COMPT.
20'³
ER EQUIP BAY
+Zc
LOWER EQUIP. BAY
L.H. EQUIPMENT BAY
+Yc
Zc 35.5

SECT A-A




LANDING IMPACT ATTENU
SYSTEM LOCATED IN THIS
ALSO CONTAINS:
a. ROLL, PITCH & YAW CON
b. FUEL & OXIDIZER FOR
CONTROL MOTORS
c. HELIUM PRESSURANT
CONTROL PROPELL
d. OXYGEN & WATER FOR


HINGED AIRLOCK
& DISCONE ANT
HATCH COVER
B
$X_C$ 106.4
32°
29.5 DIA.
T BAY
STRUCTURE
$X_C$ 55.6
ION
TRUCTURE
DE ML
23 HA
139.8 R.
TION
AREA.
$+Z_C$ 0
120 DIA
B
R.H. CREW
(90TH PERCENT
ABLATIVE HEAT SH
ROL MOTORS
ATTITUDE
OR ATTITUDE
ANTS
CREW SUPPORT

Dr

2

-HROUD
NNA

TE RECOVERY SYSTEM COMPT
20'³

AY PANEL

TCH

A
HEAT SHIELD SEPARATION PLANE
FOR LANDING IMPACT ATTENUATION

INTERIOR VOLUMES
INSIDE ML 182'³ TOTAL
EQUIP & DISPLAYS 100'³
HABITABLE 82'³

UPPER EQUIP BAY

COUCH
ILE CREWMAN)
IELD OMITTED

awing 3586-19. Two-Man, 120-Inch-Diameter Apollo Configuration



[redacted]

[redacted]

Table 15. Apollo Command Module and Service Module Equipment Weights (lb)*

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Diameter (In.) | 154 | 154 | 154 | 120 | 154 | 154 | 154 | 120 |
| Mission Time (Days) | 14 | 8 | 8 | 8 | 14 | 8 | 8 | 8 |
| Number of men | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 2 |
| Equipment | Present Apollo | | | | Advanced Electronics | | | |
| Command Module | | | | | | | | |
| Structure | 3630 | 3630 | 3630 | 2160 | 3630 | 3630 | 3630 | 2160 |
| Crew systems | 522 | 522 | 373 | 373 | 522 | 522 | 373 | 373 |
| Communication and instrumentation | 849 | 849 | 847 | 847 | 760 | 760 | 760 | 760 |
| Guidance and Navigation | 350 | 350 | 350 | 350 | 250 | 250 | 250 | 250 |
| Stabilization and control | 211 | 211 | 211 | 211 | 135 | 135 | 135 | 135 |
| Reaction control | 245 | 245 | 245 | 245 | 245 | 245 | 245 | 245 |
| Electrical power | 454 | 454 | 454 | 454 | 385 | 385 | 385 | 385 |
| Environmental | 254 | 254 | 180 | 180 | 254 | 254 | 180 | 180 |
| Earth landing | 617 | 617 | 565 | 450 | 617 | 617 | 565 | 450 |
| Useful load | 1358 | 1302 | 1033 | 965 | 1358 | 1302 | 1033 | 965 |
| Command Module | | | | | | | | |
| Gross weight | 8490 | 8434 | 7888 | 6185 | 8156 | 8100 | 7556 | 5903 |
| Service Module Equipment | | | | | | | | |
| Electronic subsystem | 120 | 120 | 120 | 120 | 139 | 139 | 139 | 139 |
| Reaction control | 737 | 737 | 737 | 737 | 641 | 641 | 641 | 641 |
| Electrical power | 1132 | 1132 | 1132 | 1132 | 983 | 910 | 910 | 910 |
| Environmental | 74 | 74 | 74 | 74 | 74 | 74 | 74 | 74 |
| Useful load | 1342 | 1229 | 1181 | 980 | 865 | 865 | 770 | 570 |
| Service Module Equipment | | | | | | | | |
| Gross Weight | 3405 | 3292 | 3244 | 3043 | 2702 | 2629 | 2534 | 2334 |
| Total Apollo payload | 11,895 | 11,726 | 11,132 | 9228 | 10,858 | 10,729 | 10,090 | 8237 |

*Based upon September 1962 Apollo weight statement



[redacted]

[redacted]

Figure 12 shows the weight injected to escape for a direct flight mission, as a function of the Apollo command module and associated service module equipment weights. Propulsion units considered included both a $LO_2/LH_2$ landing stage plus storable S/M propellants, and a cryogenic $LO_2/LH_2$ system for both the landing stage and service module. The data show that for the two-man, 8-day, 120-inch-diameter capsule employing current Apollo equipments, the requirement for cryogenic propellants to accomplish the DF mission within the C-5 launch capability is confirmed. Granted that cryogenic propellants are required for the DF mission and that the reliability of the $LO_2/LH_2$ propulsion systems can be developed in the time period of interest to a state approaching that of a storable propellant system (as shown previously), then the DF mission appears feasible with a 154-inch command module which has either a two-man crew and current Apollo equipments or a three-man crew with advanced state-of-the-art electronics available in the late 1960's. Drawing No. 3529-35 shows the arrangement for a two-man crew in a 154-inch-base-diameter capsule.

A detailed equipment layout design for the two-man DF mission in the 120-inch diameter capsule was beyond the scope of this study. However, assuming a nominal equipment packing density of 28 lb/$ft^3$ (current Apollo design data), approximately 114 $ft^3$ would be required to house the equipment and displays in this capsule. This indicates a need for a capsule somewhat larger (and heavier) than the one initially assumed as having a 120-inch base diameter.

In summary, cryogenics are needed to accomplish the two-man DF mission in the 120-inch-base-diameter command module. It would appear that the crew can be afforded significantly more "Lebensraum" and that this mission still would be feasible with present Apollo equipments in a C/M approaching 154-inches in diameter. Another alternative would be to increase the capsule size somewhat less than the full 154-inches, employing the additional weight margin to enhance reliability by increasing redundancy and the number of spare components.

To send a three-man crew directly to the moon in a 154-inch C/M (total habitable volume of 238 $ft^3$), requires advanced state-of-the-art electronics. These equipments will be available in the latter part of this decade.

[redacted]

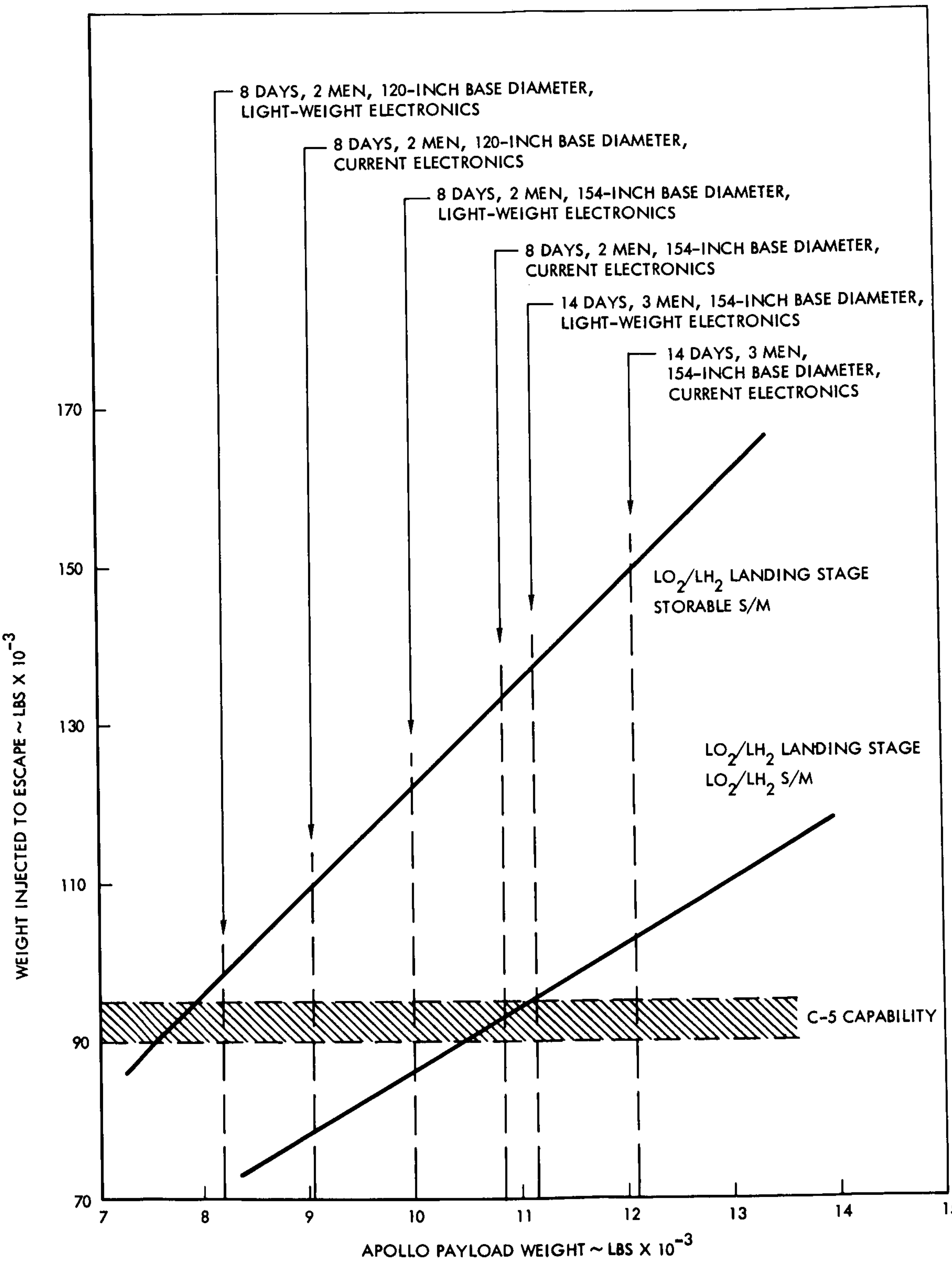
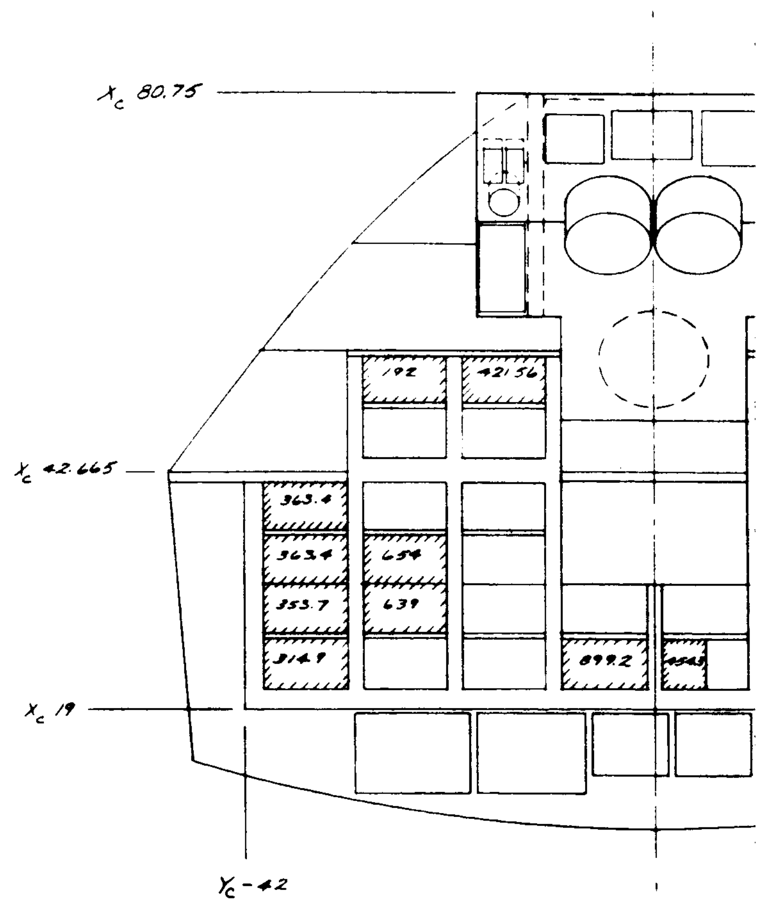



Figure 12. Weights to Escape



[redacted]

[redacted]

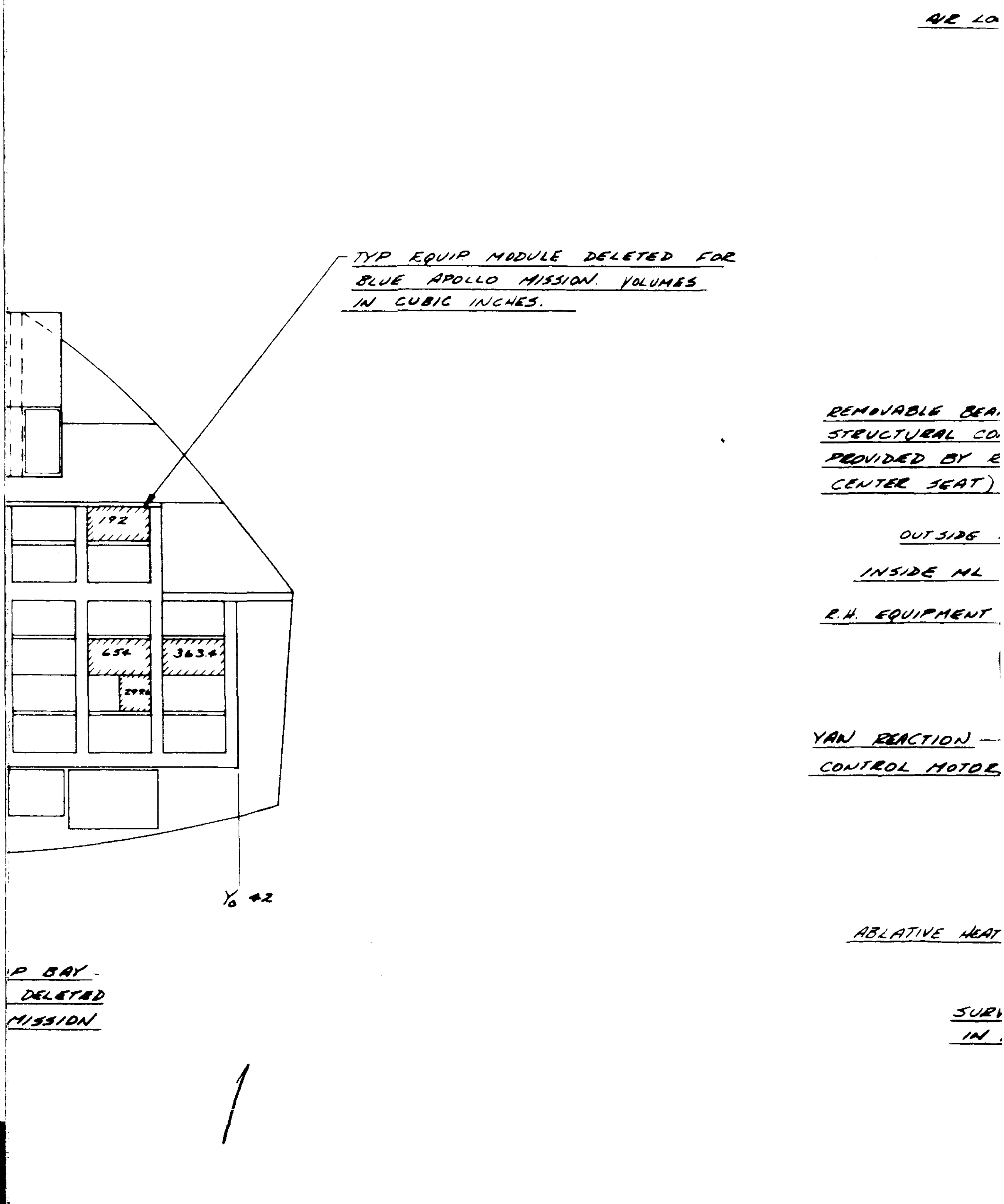



SECT A-A

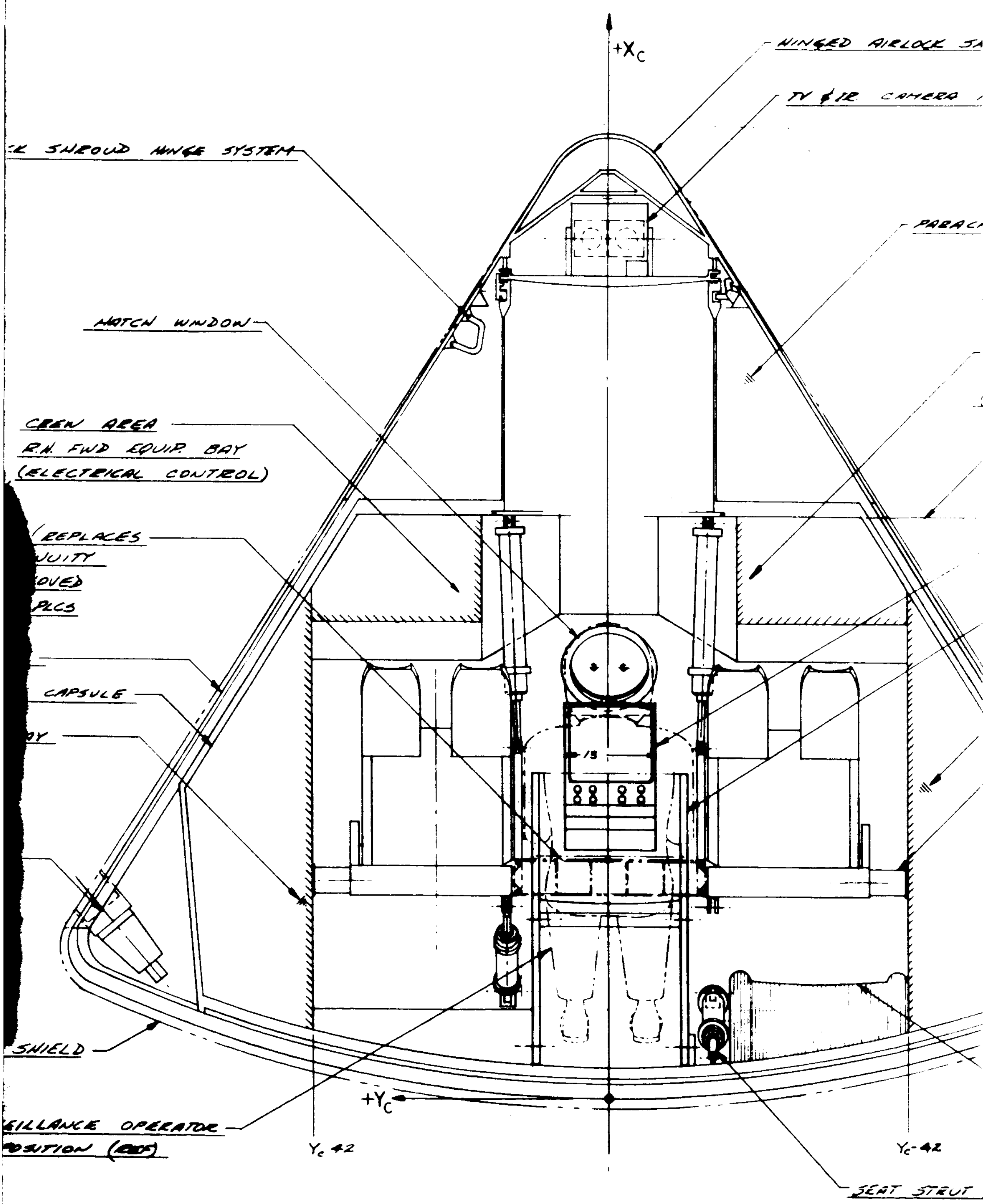
VIEW OF LOWER EQU

SHOWING EQUIP. AREAS

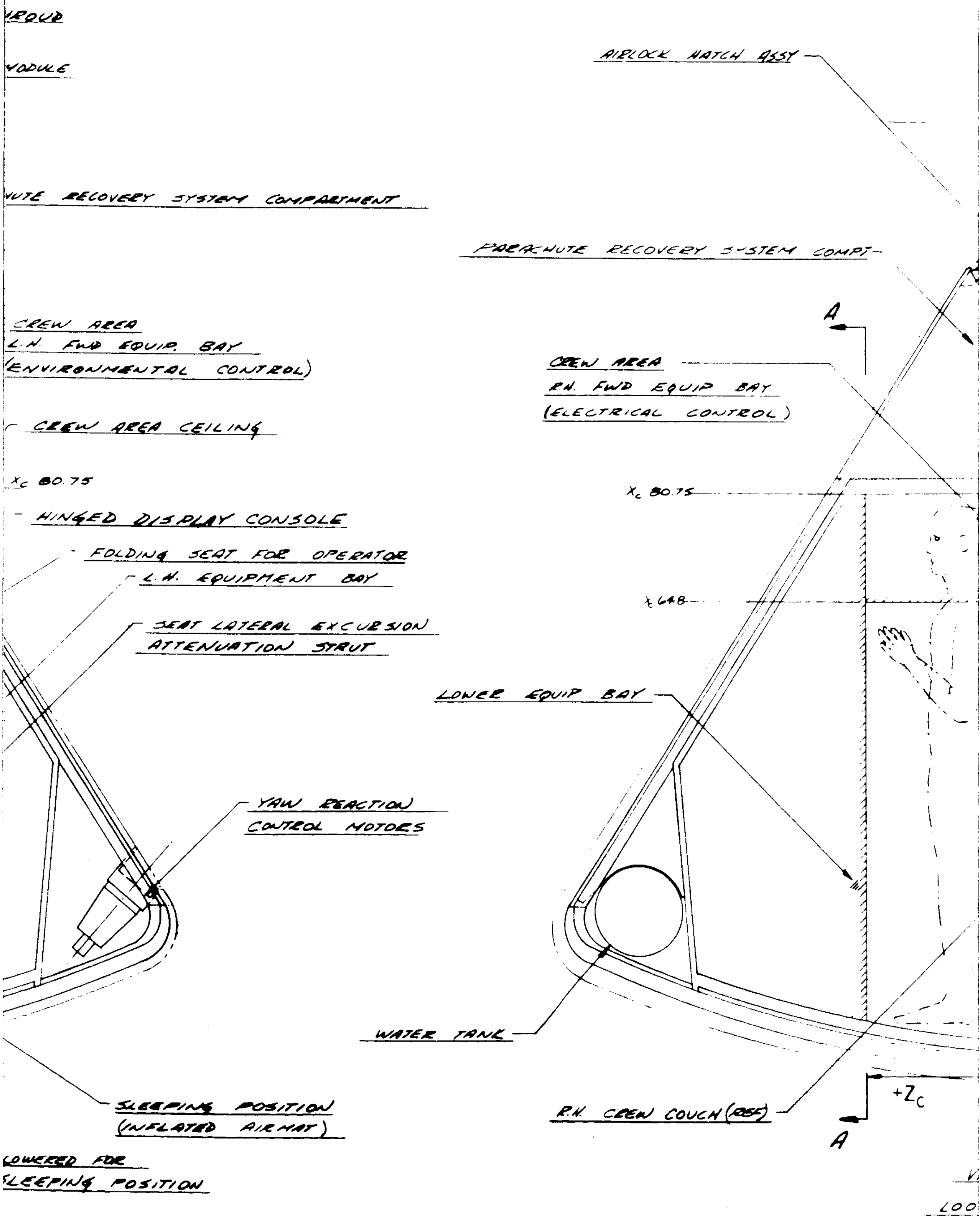
FROM BASIC APOLLO



AIR LO
TYP EQUIP MODULE DELETED FOR BLUE APOLLO MISSION. VOLUMES IN CUBIC INCHES.
192
654
363.4
REMOVABLE BEA
STRUCTURAL CO
PROVIDED BY R
CENTER SEAT)
OUTSIDE
INSIDE ML
R.H. EQUIPMENT
YAW REACTION
CONTROL MOTOR
$Y_0$ 42
ABLATIVE HEAT
P BAY
DELETED
MISSION
SURV
IN

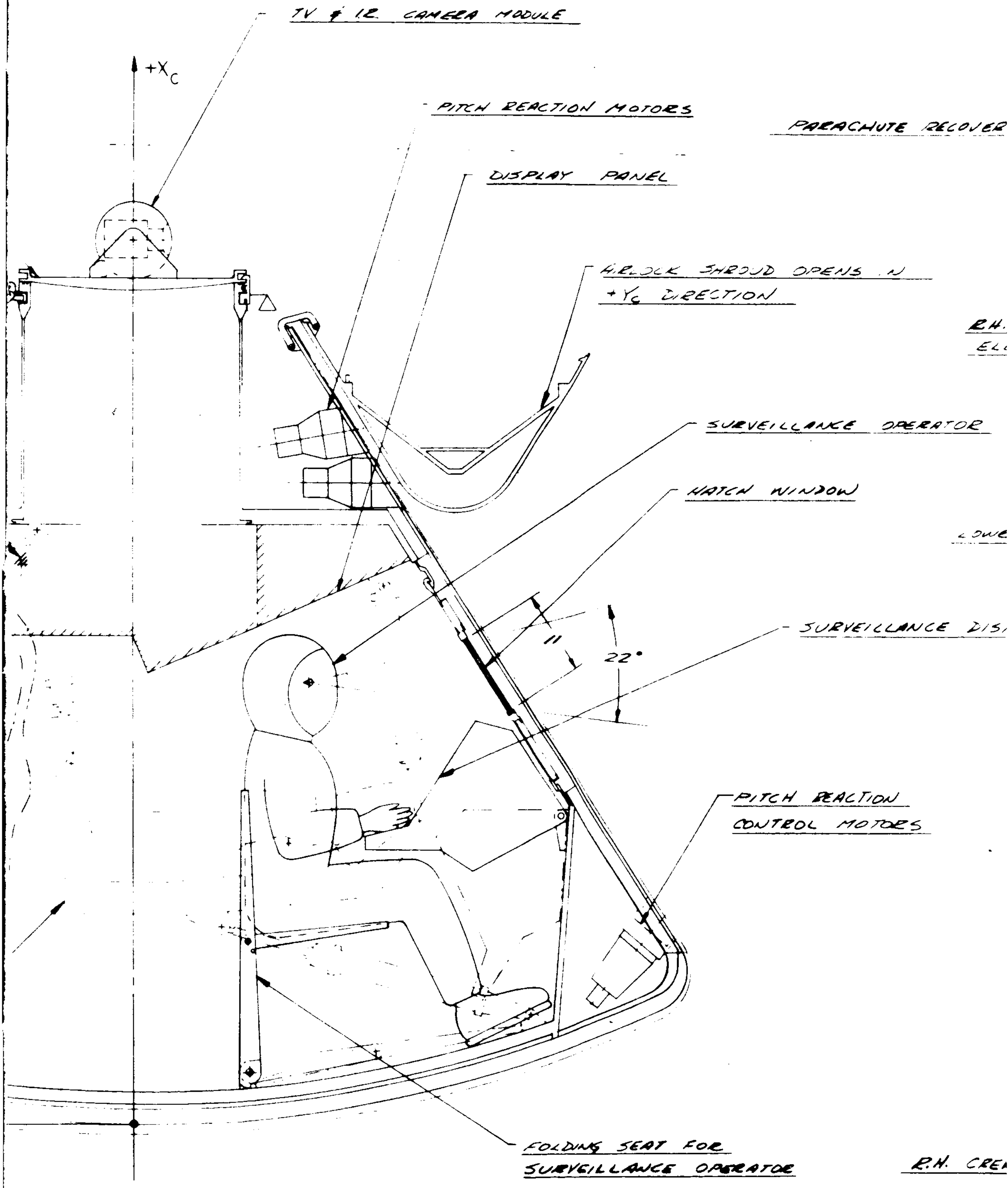



VIEW LOOKING TOWARD UPPER
END OF CREW AREA

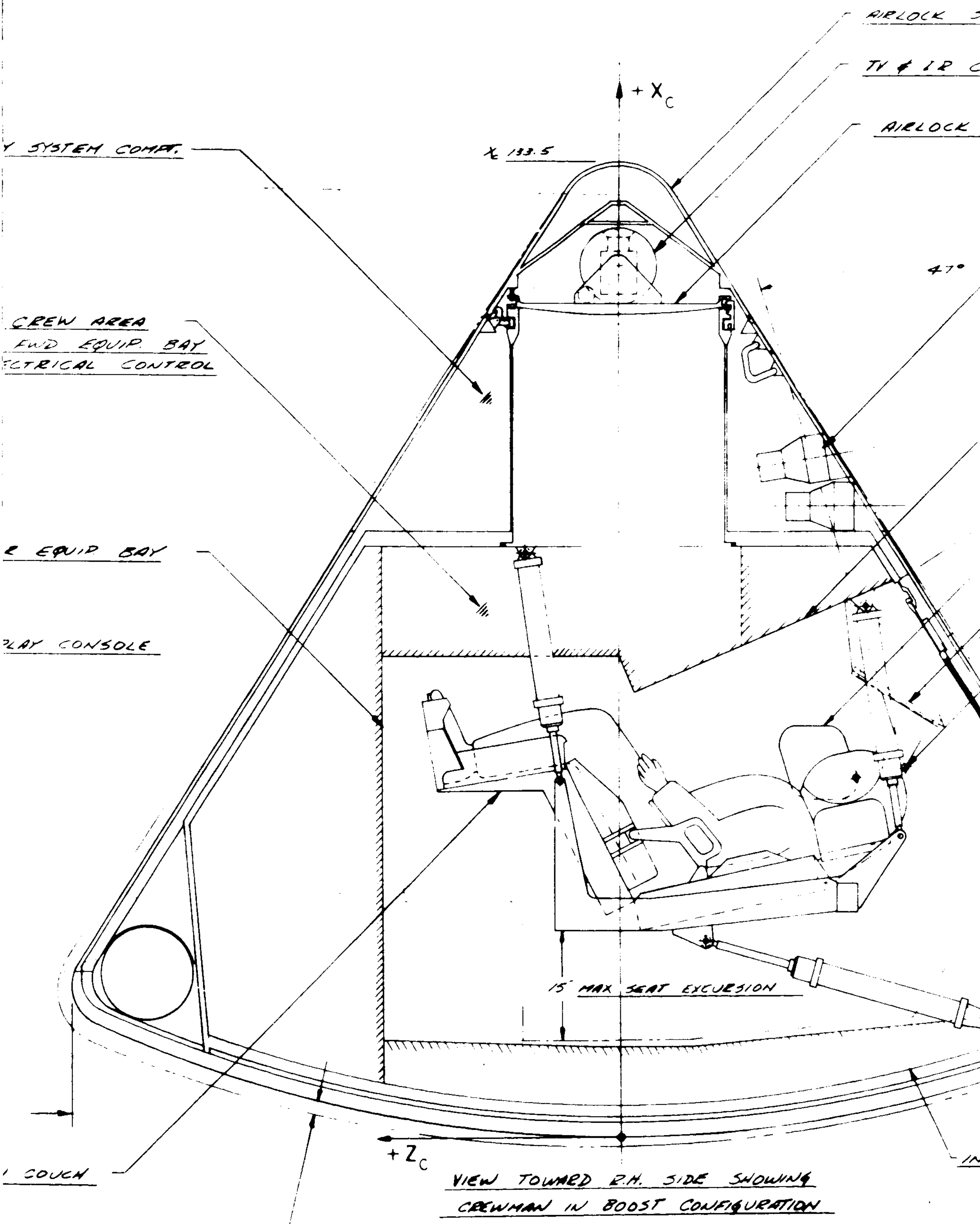


ROUD
MODULE
HUTE RECOVERY SYSTEM COMPARTMENT
CREW AREA
L.H. FWD EQUIP. BAY
(ENVIRONMENTAL CONTROL)
CREW AREA CEILING
$X_C$ 80.75
HINGED DISPLAY CONSOLE
FOLDING SEAT FOR OPERATOR
L.H. EQUIPMENT BAY
SEAT LATERAL EXCURSION
ATTENUATION STRUT
YAW REACTION
CONTROL MOTORS
SLEEPING POSITION
(INFLATED AIR MAT)
LOWERED FOR
SLEEPING POSITION
AIRLOCK HATCH ASSY
PARACHUTE RECOVERY SYSTEM COMPT
A
CREW AREA
R.H. FWD EQUIP BAY
(ELECTRICAL CONTROL)
$X_C$ 80.75
℄ 64.8
LOWER EQUIP BAY
WATER TANK
R.H. CREW COUCH (REF)
$+Z_C$
A


2



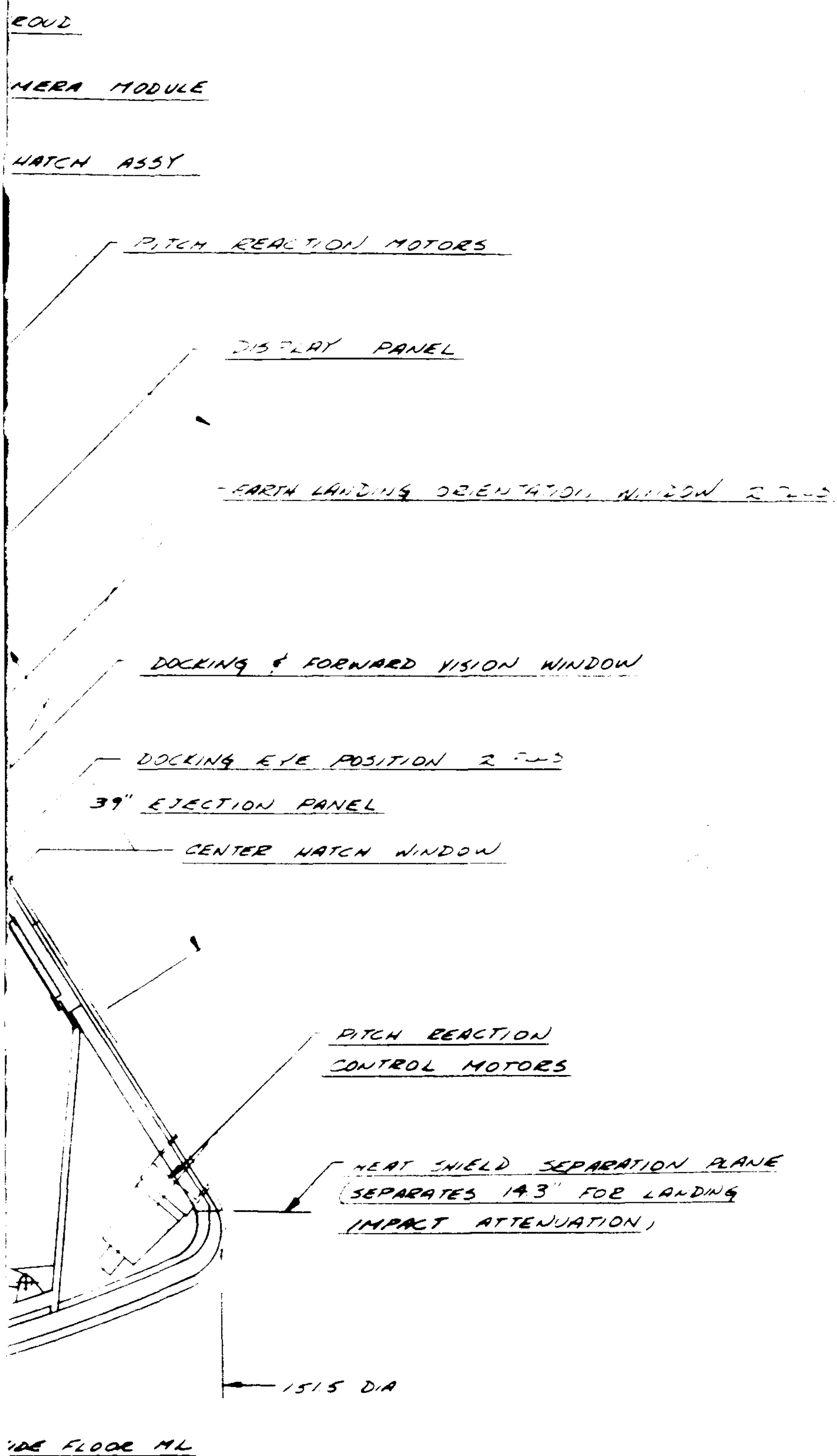

IEW THRU CAPSULE CENTER
KING TOWARD R.H. SIDE ($+Z_c$)




VIEW TOWARD R.H. SIDE SHOWING
CREWMAN IN BOOST CONFIGURATION

Drawing 35
Direct

3




29-35. Apollo Interior Arrangement—Two-Man,
Flight, 154-Inch-Diameter Command Module



[redacted]

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# APPENDIX A - SPACECRAFT FUNCTION ABBREVIATION LIST

| | |
|---|---|
| AC | Alternating Current |
| C/M | Command Module |
| CS | Crew Safety |
| ECS | Environment Control System |
| IMU | Inertial Measurement Unit |
| EPS | Electrical Power System |
| GOSS | Ground Operational Support System |
| LEM | Lunar Excursion Module |
| LET | Launch Escape Tower |
| LLM | Lunar Landing Module |
| LOR | Lunar Orbital Rendezvous |
| MS | Mission Success |
| N&G | Navigation and Guidance System |
| RCS | Reaction Control System |
| S/C | Spacecraft |
| SCS | Stabilization and Control System |
| S/M | Service Module |



[redacted]